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DETERMINATION OF LAYER MODULI FROM FALLING WEIGHT DEFLECTOMETER TESTS

This Master's thesis has been submitted for official examination for the degree of Master of Science in Helsinki University of Technology, Faculty of Civil Engineering and Surveying, Department of Structural Engineering, Espoo, Finland.

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Backcalculation programs are used for evaluation of pavement layer moduli from falling weight deflectometer (FWD) measurements. In this study, a comparison of two programs with different calculation methods, Modulus and Elmod, is made using deflection data derived from 43 SHRP-LTPP (Strategic Highway Research Program, Long-Term Pavement Performance) test sections.

First, a brief look is made into the theoretical behaviour of pavement layer materials and existing material models. Basic concepts of the two backcalculation programs used in this study, Modulus and Elmod, are discussed, and collection of input data for the programs is described.

From a comparison of backcalculated layer moduli from the two programs at Finnish standard wheel load of 50 kN, it is concluded that higher subgrade modulus values are obtained with the Elmod-program than with the Modulus-program. Consequently, the Modulus-program yields higher values for asphalt layer modulus than the Elmod-program. Variation in backcalculated layer moduli is somewhat greater within the Modulus-program than the Elmod-program.

Stress-sensitivity of paving materials was studied by using the FWD at four different loading levels. The base course modulus was found to be the most stress-sensitive of pavement layers, since the stress level is also highest in the base course of unbound pavement layers.

Critical strains were calculated using the linear program (BISAR) with layer moduli from the Modulus-program as input and with the Elmod-program. It was found, that calculated strains from the two programs agree very well, even though the calculated moduli are quite different. Compared with strains and deflections measured in the field at an instrumented pavement section at Virttaa test site, a certain discrepancy was found between the two.

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Takaisinlaskentaohjelmia käytetään tien rakennekerrosten muodonmuutosmoduulien määrittämiseen pudotuspainolaitteella mitatuista taipumasuppiloista. Tässä tutkimuksessa verrataan kahden takaisinlaskentaohjelman, Moduluksen ja Elmodin, antamia tuloksia. Laskelmat tehtiin 43 SHRP-LTPP (Strategic Highway Research Program, Long-Term Pavement Performance) kohteessa tehdyistä mittauksista.

Ensin kuvataan lyhyesti tien rakennekerrosmateriaalien teoreettista käyttäytymistä ja materiaalimalleja. Takaisinlaskentaohjelmien laskentaperiaatteita kuvataan lyhyesti, samoin mittaustietojen keruumenetelmiä.

Takaisinlaskettuja kerrosmoduuleja standardipyöräkuormalla (50 kN) verrattaessa havaitaan, että Elmod-ohjelmalla saadaan korkeampia pohjamaan moduulin arvoja kuin Modulus-ohjelmalla. Modulus-ohjelmalla saadaan vastaavasti korkeampia asfaltin moduulin arvoja kuin Elmod-ohjelmalla. Kerrosmoduulien hajonta on Modulus-ohjelmalla jonkin verran suurempaa kuin Elmod-ohjelmalla.

Rakennekerrosmateriaalien jännitysriippuvuutta tutkittiin tekemällä pudotuspainomittaukset neljällä eri pudotuskorkeudella. Kantavan kerroksen jännitysriippuvuus osoittautui rakennekerroksista suurimmaksi, koska siihen kohdistuva jännitys on selvästi suurempi kuin muihin sitomattomiin kerroksiin kohdistuva jännitys.

Kriittiset muodonmuutokset laskettiin lineaaris-elastisella monikerrosohjelmalla (BISAR) käyttäen lähtötietoina Modulus-ohjelmalla määritettyjä kerrosmoduulien arvoja. Näitä verrattiin Elmod-ohjelmalla laskettuihin muodonmuutoksiin. Kahdella eri ohjelmalla lasketut muodonmuutokset vastasivat hyvin toisiaan, vaikka takaisinlasketuissa kerrosmoduulien arvoissa oli huomattaviakin eroja. Laskettuja muodonmuutoksia ja taipumia verrattiin Virttaan koekentällä mitattuihin muodonmuutoksiin ja taipumiin. Laskettujen ja mitattujen suureiden välillä havaittiin tiettyjä eroavaisuuksia.

PREFACE

The Technical Research Centre of Finland (VTT) and The Finnish Road Administration (FinnRA) are collaborating with the international SHRP-LTPP program (Strategic Highway Research Program, Long-Term Pavement Performance). As part of the Finnish study, falling weight deflectometer (FWD) measurements were carried out at 43 test sections. Layer moduli and critical strains were determined to be used as input for the development of new mechanistic models describing pavement deterioration.

Pavement layer moduli were determined using two programs for comparison purposes. Theoretical pavement behaviour and calculation methods used in the programs are briefly discussed and the results are presented.

I want to thank the supervisor and instructor of my thesis, Professor Eero Slunga and Lis.Tech. Heikki Jämsä, respectively, for the guidance and advice during the research process. I also want to express great gratitude to my colleagues at the Technical Research Centre of Finland (VTT) for data collection, technical help with the publication of this paper and all the numerous discussions about the art of pavement evaluation. Your effort has made the completion of this study possible.

Espoo, 14 January, 1994

Antti Ruotoistenmäki

LIST OF SYMBOLS AND ABBREVIATIONS

ε	critical strain, µm/m
ε^p	plastic portion of strain, µm/m
ε^e	elastic (resilient) portion of strain, µm/m
ε^t	total strain, $\varepsilon^t = \varepsilon^p + \varepsilon^e$, µm/m
ε	error between measured and calculated deflections
μ	Poisson's ratio
μ_i	Poisson's ratio of a pavement layer
μ_m	Poisson's ratio of the underlying layer
σ	stress, kPa
θ	bulk stress, sum of principal stresses, kPa
σ_1, σ_2, σ_3	principal stresses, kPa
σ_1	major principal stress, kPa
σ'	reference stress, kPa
τ_{oct}	octahedral shear stress, kN/m^2
avg	average
c	damping ratio of dashpot
h	pavement layer thickness, mm
h_e	equivalent thickness of the layer, mm
h_g	granular layer thickness, mm
k	spring coefficient
k_1, k_2, k_3, k_4	regression coefficients
n	correction factor, n=0,8-1,0
n	coefficient
p	loading, kN
r	deflector distance from loading plate, mm
std	sample standard deviation
t	loading time, s
C_0	coefficient
CV	coefficient of variation of layer materials, %
D_3	surface deflection at 914 mm (3 ft), µm
D_r	surface deflection at distance r, µm
E	modulus of elasticity of pavement layer materials, MN/m^2
E_i	modulus of a layer, MN/m^2
E_g	granular layer modulus, MN/m^2
E_m	modulus of the underlying layer, MN/m^2
E_s	subgrade modulus, MN/m^2
E_{sg}	subgrade modulus, MN/m^2
$E_{Modulus}$	backcalculated layer modulus from the Modulus-program, MN/m^2
E_{Elmod}	backcalculated layer modulus from the Elmod-program, MN/m^2

EI	stiffness of pavement layer, MNm^2
I	moment of inertia, m^4
M_r	resilient modulus of pavement layer materials, MN/m^2
N	number of load applications to reach pavement failure
P	load, kPa
PI	penetration index of bitumen
S	stiffness modulus of bitumen, MN/m^2
T_{800}	softening point of bitumen
W_i^c	computed deflection at sensor i
W_i^m	measured deflection at sensor i
We_i	weighting factor for sensor i
BISAR	A linear elastic multi-layer computer program to calculate stresses, strains and deflections in pavement structure
ELMOD	A computer program for backcalculation of in-situ pavement layer moduli from measured deflections, uses method of equivalent thicknesses and Boussinesq's equations
FinnRA	Finnish Road Administration
FWD	Falling Weight Deflectometer
GPS	General Pavement Studies, SHRP-LTPP test section types
LTPP	Long-Term Pavement Performance, a subproject of SHRP-program extending to year 2007
MET	Method of Equivalent Thicknesses
MODULUS	A computer program for backcalculation of in-situ pavement layer moduli from measured deflections, uses linear elastic theory
NDT	Non-destructive testing devices, such as the falling weight deflectometer
SHRP	Strategic Highway Research Program, a six-year (1987-1993) pavement research program carried out in the USA
VTT	Technical Research Centre of Finland
WES5	A linear elastic multi-layer computer program to calculate stresses, strains and deflections in pavement structure

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1 INTRODUCTION

The use of analytical methods is becoming more widespread in pavement design. These methods are usually based on the concept of fatigue, which is commonly expressed in terms of a fatigue curve of the form (Figure 1):

$$N=k_1\left(\frac{1}{\varepsilon}\right)^{k_2} \tag{1}$$

where	N is	number of load applications to reach failure
	ε	critical strain
	k_1, k_2	coefficients

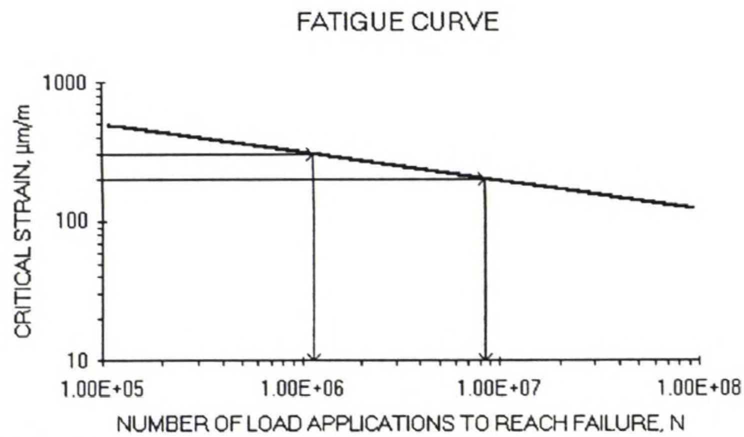


Figure 1. Concept of fatigue in pavement design.

Horizontal tensile strain at the bottom of the bituminous layer and vertical compressive strain on the top of the subgrade are considered as critical strains that control pavement life (Figure 2). The former parameter describes fatigue cracking in the asphalt layer, and the latter, permanent deformation in the subgrade [1].

Elastic moduli and thicknesses of pavement layers are used as input to design procedures. The implementation of new design methods calls for accurate determination of pavement layer properties. In-situ material parameters for paving materials can be evaluated from deflection data of non-destructive testing (NDT) devices, such as the falling weight deflectometer (FWD).

The falling weight deflectometer simulates the effect of wheel load on pavement structure. A falling mass causes a dynamic load on the pavement structure and

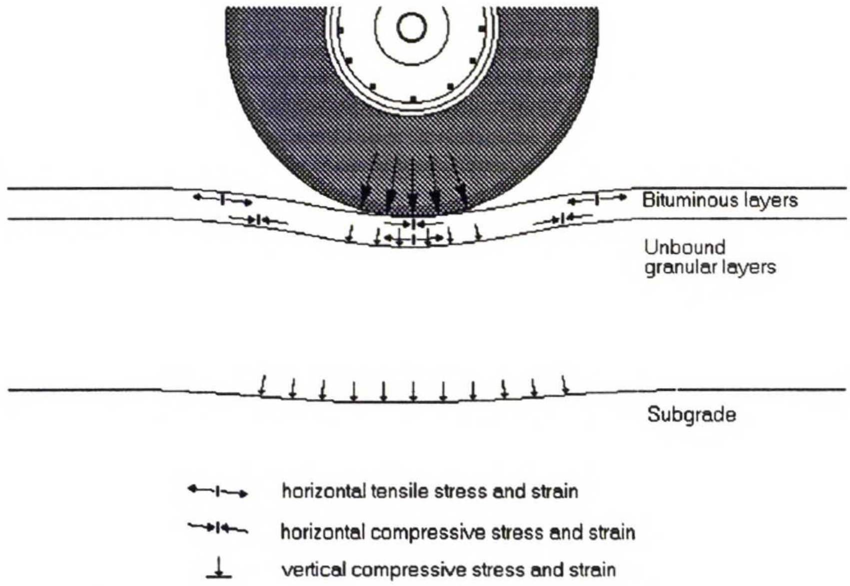


Figure 2. Critical strains under moving wheel load.

hence surface deflections (Figure 3). Deflection is measured below the loading plate and at certain distances from the loading plate. Elastic layer moduli are backcalculated from the measured deflection bowl.

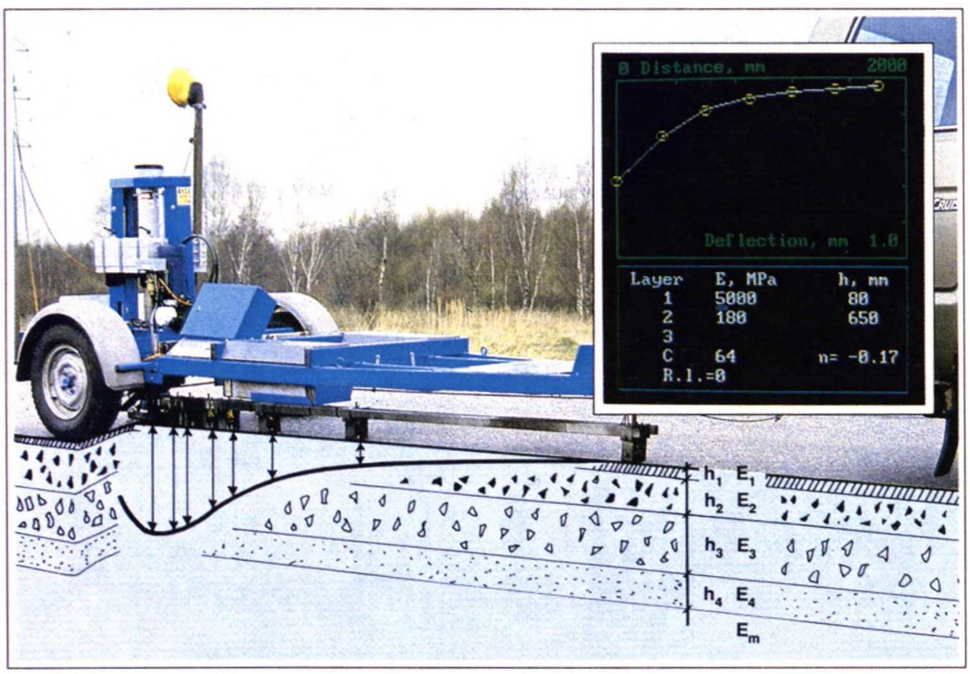


Figure 3. Falling weight deflectometer (FWD).

2 OBJECTIVES

The objective of this study is to determine and compare the backcalculated layer moduli from two different programs, Modulus [2] and Elmod [3]. The analysis is based on the falling weight deflectometer data derived from in-service pavements.

Modulus uses linear elastic theory, and it is one of the methods used in the Strategic Highway Research Program (SHRP). Elmod is based on the method of equivalent thicknesses (MET) and Boussinesq's equations, and was chosen for this study because of its different analysis approach.

In addition, the effect of stress level on the layer moduli is examined. Deflection measurements were carried out at four different loading levels, and layer moduli at each loading level were backcalculated.

A comparison of critical strains is carried out by using two different calculation methods. Strains were forward-calculated by the linear elastic multi-layer program (BISAR) [4], using the backcalculated moduli from Modulus. They are compared with the strains forward-calculated by Boussinesq's equations within the Elmod-program. The calculated strains are validated through a comparison with the strains measured at an instrumented in-field pavement section.

No attention was paid to other features of the programs, such as calculation of residual life and the overlay thickness needed.

3 LAYER MATERIAL MODELS

3.1 LINEAR ELASTIC MULTI-LAYER THEORY

Multi-layer theory is widely used to describe the behaviour of pavement structure. The modelling of the pavement structure is illustrated in Figure 4 and assumptions of the theory are as follows [1]:

1. Layer properties are usually described using two parameters, modulus, E, and Poisson's ratio, μ. Materials are assumed linear elastic.

2. All layers are isotropic and homogeneous. This means that their properties are similar in all directions and at all locations.

3. Wheel load is represented by uniformly distributed pressure over a circular contact area.

4. Pavement structure consists of layers extending to infinity in horizontal direction with constant thickness and zero unit weight. Subgrade extends infinitely downwards.

5. Full friction is usually assumed at all layer interfaces making horizontal strain compatible.

In addition to modulus and Poisson's ratio, layer thickness, h, is a third variable describing the behaviour of a layered system (Figure 4). Two of these three variables must be set in order to solve the third, using backcalculation programs. Layer thicknesses can be known quite accurately from test pits. Poisson's ratio can be estimated reasonably well for each material, and it has a minor effect on pavement behaviour. This leaves layer modulus to be solved.

In-service pavement structures typically consist of four to six layers including the subgrade. For practical purposes, pavements are usually described in terms of three- or four-layer structures. A stiff layer taking into account the presence of rock or stiffening of subgrade with depth, may be incorporated in the elastic layer theory.

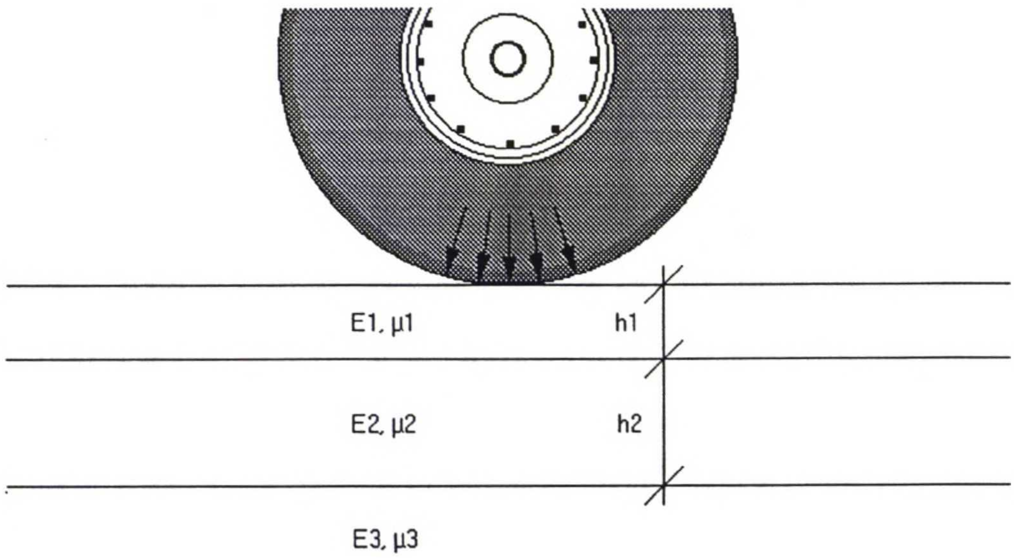


Figure 4. Linear elastic multi-layer theory. Configuration of layers and loading conditions.

The layer theory has been found to be reasonably valid. Some comments may be introduced, however. First, paving materials do not behave linear elastically. This is further discussed in the following chapters. Secondly, static loading conditions do not take the transient nature of traffic loading into consideration. This may cause overestimation of the backcalculated layer moduli, as will be discussed in chapter 7.1. And finally, in the longitudinal direction of the road, the assumption of layers extending to infinity in a horizontal direction may be judged reasonable, but in a transverse direction, the effect of the pavement edge is neglected.

3.2 DEFINITIONS OF MODULI

The stress-strain relationship of a material may be described in three different ways (Figure 5, [5]):

a) linear or non-linear
b) elastic (ε^e) or plastic (ε^p)
c) viscous (time-dependent) or non-viscous

Definitions of different moduli are given in Figure 6. The linear elastic modulus (Figure 6a) is defined as the ratio of stress increment to strain increment:

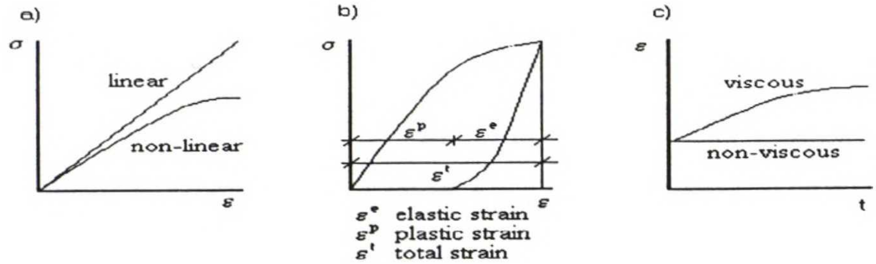


Figure 5. Stress-strain (σ-ε) relationship of a material [5].

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{2}$$

The stress-strain relationship is constant at all stress levels. The non-linear elastic modulus is a tangent modulus (Figure 6b) describing the stress-strain relationship closely over the whole stress-strain curve:

$$E = \frac{d\sigma}{d\varepsilon} \tag{3}$$

The modulus of granular material is often described as resilient modulus, M_r, defined as the ratio of stress increment to resilient strain (Figure 6c):

$$M_r = \frac{\Delta\sigma}{\Delta\varepsilon^e} \tag{4}$$

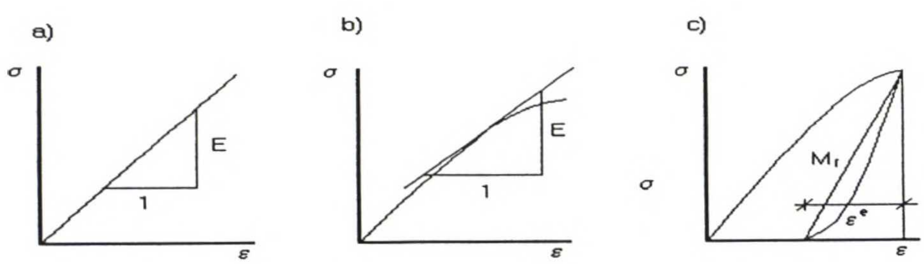


Figure 6. Definition of material moduli.

3.3 VISCOUS BEHAVIOUR OF ASPHALT CONCRETE

Bitumen is a viscous material; its modulus value decreases with increasing temperature and loading time. Raising the temperature amplifies the viscous properties of bitumen. Asphalt concrete is a mixture of bitumen and granular material and therefore combines the properties of both materials.

The ideal material models which describe the behaviour of a material are elastic and viscous material models (Figure 7). The linear elastic behaviour of material is described with a spring. A viscous material is described as a dashpot.

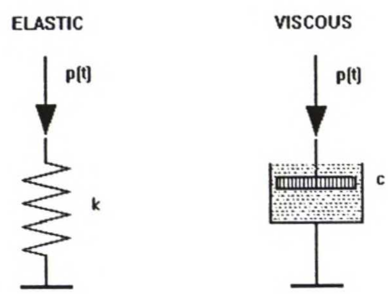


Figure 7. Elastic and viscous material models [6].

The behaviour of asphalt concrete may be modelled with a combination of these two material models. The spring and the dashpot may be joined in series or in parallel, and Maxwell and Kelvin material models are obtained, respectively (Figure 8). Under transient loading or low temperatures the material seems stiff. Under sustained loading or high temperatures the same material acts more like a fluid, with the spring receiving the loading. Other, more accurate material models have been developed, which incorporate several springs and dashpots, but they are too complex for any practical use.

The stiffness modulus of bitumen may be determined with the help of a nomograph. Van der Poel's nomograph is shown as an example in Figure 9 [7]. The stiffness modulus of bitumen depends on loading time, softening point and penetration index of bitumen.

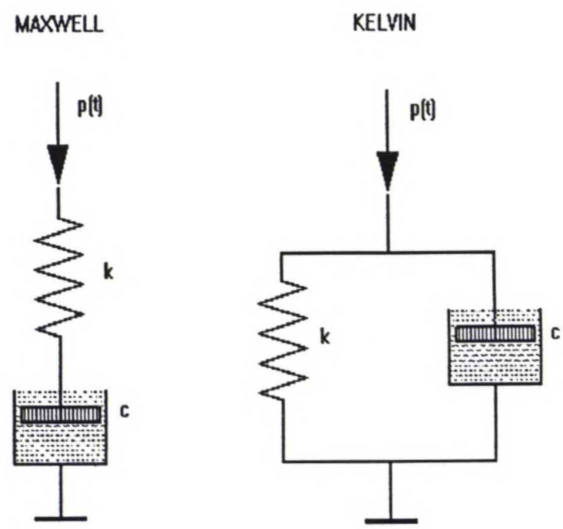


Figure 8. Maxwell and Kelvin viscoelastic material models [6].

Traffic loading is transient in nature with loading time of about 65 ms in surface layer. Therefore, the error introduced in approximating asphalt concrete behaviour with linear elastic modulus is decreased, especially at low temperatures [1].

It will be seen in chapter 8 that the backcalculated asphalt modulus seems to increase with increasing loading level. This may be due to the mathematical properties of the linear elastic and the static backcalculation method rather than the actual non-linear behaviour of bituminous material.

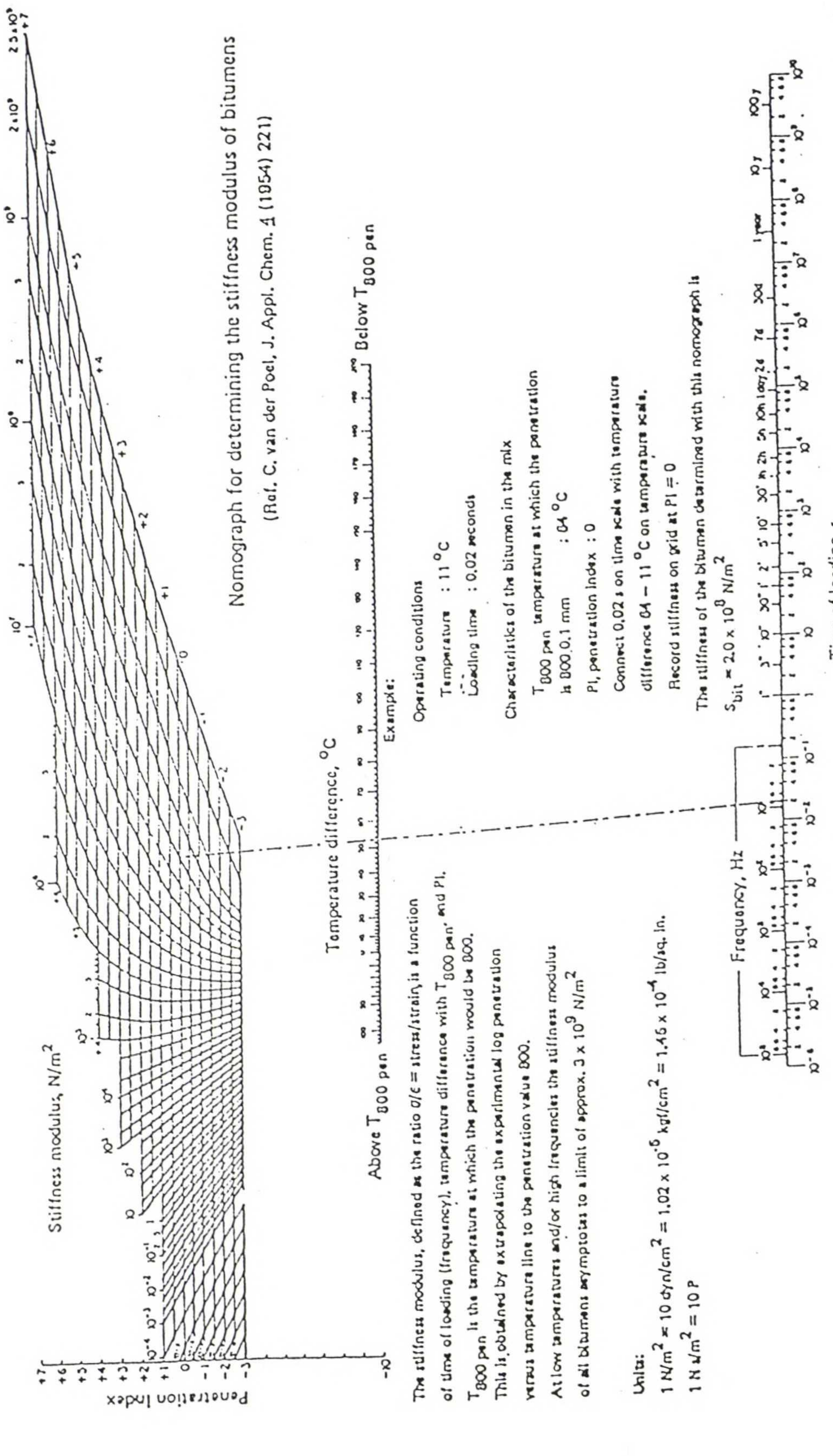


Figure 9. Van der Poel's nomograph for determination of stiffness modulus of bitumen [7].

3.4 NON-LINEAR BEHAVIOUR OF GRANULAR AND COHESIVE MATERIALS

Granular and cohesive materials found in unbound layers and subgrade exhibit non-linear behaviour. Presently, widely used models for granular and cohesive materials are stated as [5]:

$$M_r = k_1(\theta)^{k_2} \tag{5}$$

$$M_r = k_3(\tau_{oct})^{-k_4} \tag{6}$$

where	M_r is	resilient modulus, kN/m^2
	θ	bulk stress, kN/m^2
	τ_{oct}	octahedral shear stress, kN/m^2
	k_1, k_2, k_3, k_4	regression coefficients

Bulk stress and octahedral shear stress are illustrated in Figure 10. Bulk stress is the sum of the principal stresses. Octahedral shear stress is the shear stress acting on the surface of an octahedron.

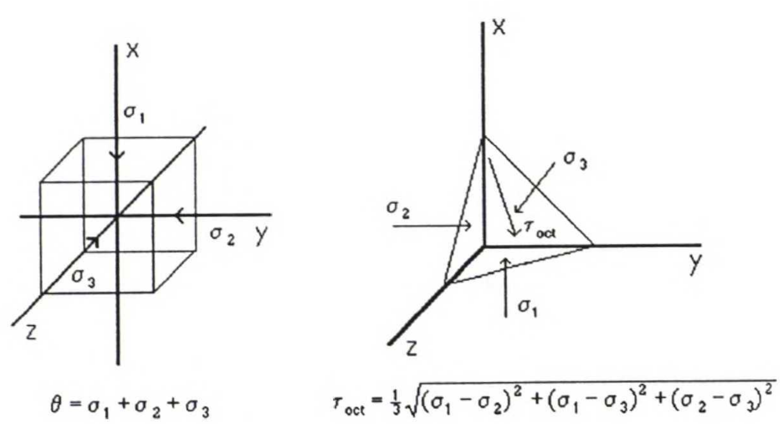


Figure 10. Definitions of bulk stress and octahedral shear stress [5].

This model yields increasing resilient modulus values with increasing stress level for granular materials. The behaviour of granular material is illustrated in Figure

11 [5]. The resilient modulus of cohesive materials decreases rapidly with increasing loading level. The behaviour of cohesive material is illustrated in Figure 12 and can also be stated by the equations [5]:

$$M_r = K_2 + K_3[K_1 - (\sigma_1 - \sigma_3)], \quad K_1 > (\sigma_1 - \sigma_3) \tag{7}$$

$$M_r = K_2 + K_4[(\sigma_1 - \sigma_3) - K_1], \quad K_1 < (\sigma_1 - \sigma_3) \tag{8}$$

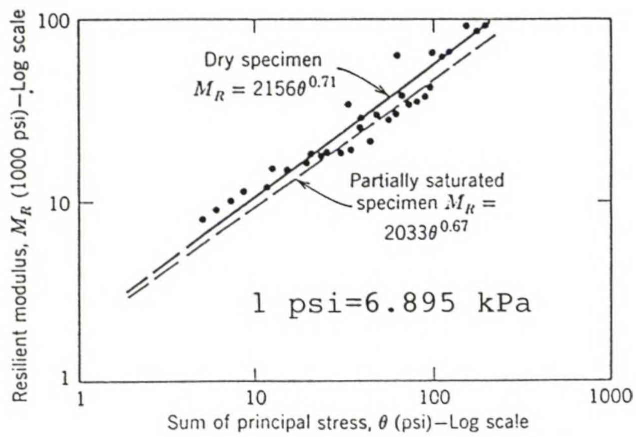


Figure 11. Typical resilient modulus (M_r) response for granular materials [5].

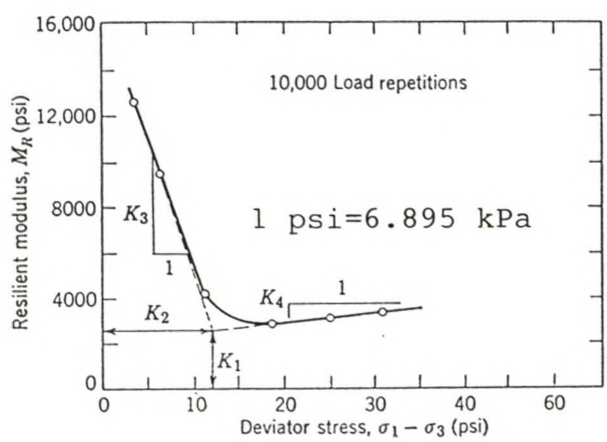


Figure 12. Typical resilient modulus (M_r) response for cohesive material [5].

However, based on recent field and laboratory studies [9,10], shear stresses decrease the resilient modulus of both cohesive and granular materials. Increasing confining pressure increases the resilient modulus of granular materials. The material model for both granular and cohesive materials can therefore be stated as [9]:

$$M_r = k_1(\theta)^{k_2}(\tau_{oct})^{-k_3} \tag{9}$$

For cohesive soils, k_2=0, and the model is reduced to the presently widely used model for cohesive material. In most pavement structures, bulk stresses are caused by overburden stresses, and shear stresses are due to traffic loading [9].

Backcalculation programs used in this study calculate linear elastic pavement layer and subgrade moduli and do not incorporate any of the material models presented here. If subgrade non-linearity is taken into account, it takes place using procedures described below.

4 BACKCALCULATION PROGRAMS USED IN THE ANALYSIS

4.1 GENERAL

For the interpretation of falling weight deflectometer results there are several backcalculation programs with different calculation methods. Therefore, different results are obtained with different programs, and sometimes even by different users using the same program. The backcalculated surface layer (asphalt concrete) and subgrade moduli are generally more reliable than the backcalculated unbound granular base and subbase layer moduli.

The two backcalculation programs compared in this study, Modulus and Elmod, apply a different analysis approach. The principles of both programs are described shortly in the following. Detailed descriptions of the programs are presented in references [2,3].

4.2 MODULUS

Modulus is a database-type backcalculation program in which a deflection bowl database is generated with the linear elastic multi-layer program (WES5). Layer moduli bounds given by the user serve as input to the linear elastic program [11]. Each measured deflection bowl is then compared with the bowls in the database and an interpolation technique is applied to obtain a set of layer moduli which minimizes squared error between measured and calculated deflections [11]:

$$\varepsilon^2=\sum [1-\frac{W_i^c}{W_i^m}]^2 * We_i \tag{10}$$

where	ε^2 is	squared error
	W_i^c	computed deflection at sensor i
	W_i^m	measured deflection at sensor i
	We_i	weighting factor for sensor i

A simplified flow chart for the Modulus-program is presented in Figure 13 [11]. After the input of layer thicknesses and bounds for layer moduli, the deflection bowl database is calculated with the linear elastic program (WES5). For each measured deflection bowl, the error between the measured bowl and all the database bowls is calculated. A check for true minimum (convexity) is made. A set of layer moduli giving minimum error between the measured and calculated deflections is set as "seed moduli" and transferred to X_i values for the Hooke-Jeeves pattern search algorithm. The three-point Lagrance interpolation is used iteratively to find the minimum of the objective function (equation (10)). The Hooke-Jeeves pattern search algorithm is known to always converge, although not always at the true function minimum [11]. The results are written to a file for further processing.

Surface deflections are due to deformations in the stress zone (Figure 14 [12]). Deflection at any offset from the load is a result of the deflection below a certain depth in the pavement. If a stiff layer exists at some depth, no surface deflection will occur beyond the offset at which the stress zone and the stiff layer intercept. The apparent depth of this rigid layer is determined from the measured deflection bowls [12]. The apparent depth of the rigid layer may also result from an increase in subgrade stiffness due to the stress-sensitive behaviour of soils, described in chapter 3.4.

The subgrade affects the whole deflection bowl (Figure 15, [13]), and its modulus is determined on the basis of all the sensors within the Modulus-program. A weighting factor We_i between 1 and 0 is assigned to each sensor. Greatest emphasis is given to the inner sensors, because the subgrade, as a stress-sensitive material, is at its weakest below the loading plate.

4.3 ELMOD

Elmod is an iterative backcalculation program. No multi-layer program is included. Calculated deflections are obtained with Boussinesq's equations. No seed value or bounds for moduli are given by the user. The only user-supplied information of the structure are the layer thicknesses, and, optionally, the depth to a rigid layer and a fixed value for the stiffness modulus of the asphalt layer. A simplified flow chart for the Elmod-program is presented in Figure 16. Measured deflection bowls are read from a formatted data file. The parameter file contains information about climate and traffic (mainly for the calculation of residual life), which can be altered through program menus.

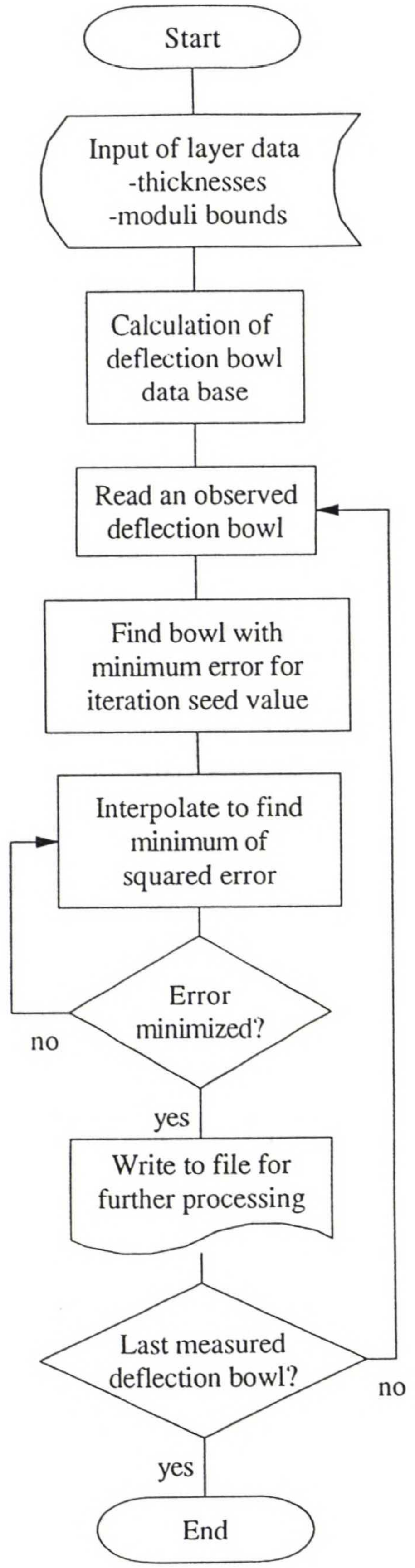


Figure 13. Simplified flow chart for Modulus-program [11].

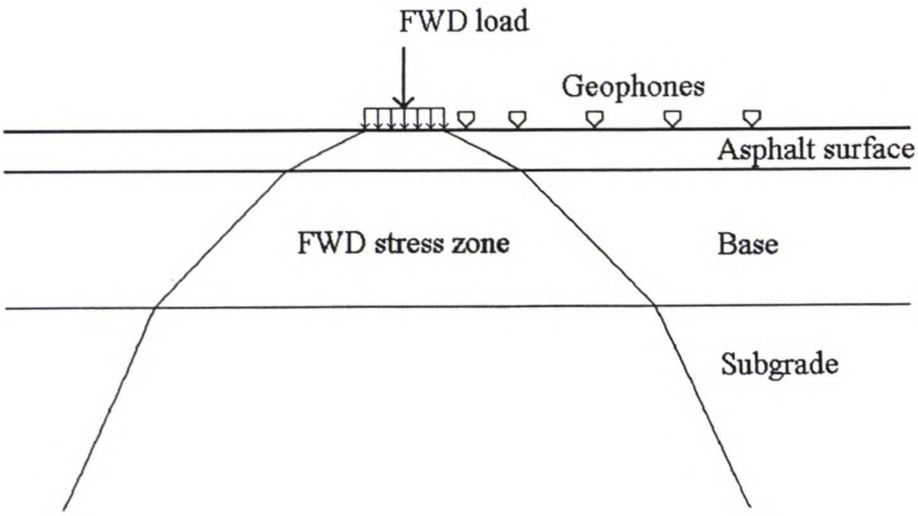


Figure 14. Stress distribution below an FWD load [11].

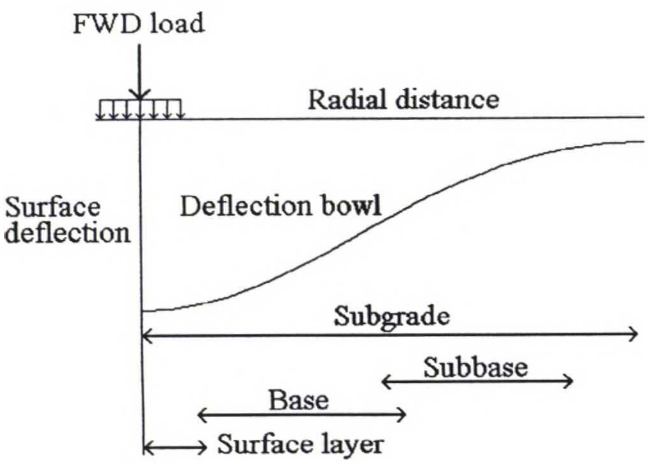


Figure 15. Effect of pavement layers to deflection bowl [13].

For each deflection bowl, iteration procedure takes place in order to determine the layer moduli. Boussinesq's equations are applied to a semi-infinite linear elastic half-space which is taken to be homogeneous and isotropic. The layered pavement structure is therefore transferred into an equivalent semi-infinite half-space with the use of Odemark's equation, see Figure 17 [14,3]:

$$h_e = n * h_i * \sum_i \sqrt[3]{\frac{E_i * (1-\mu_m^2)}{E_m * (1-\mu_i^2)}} \tag{11}$$

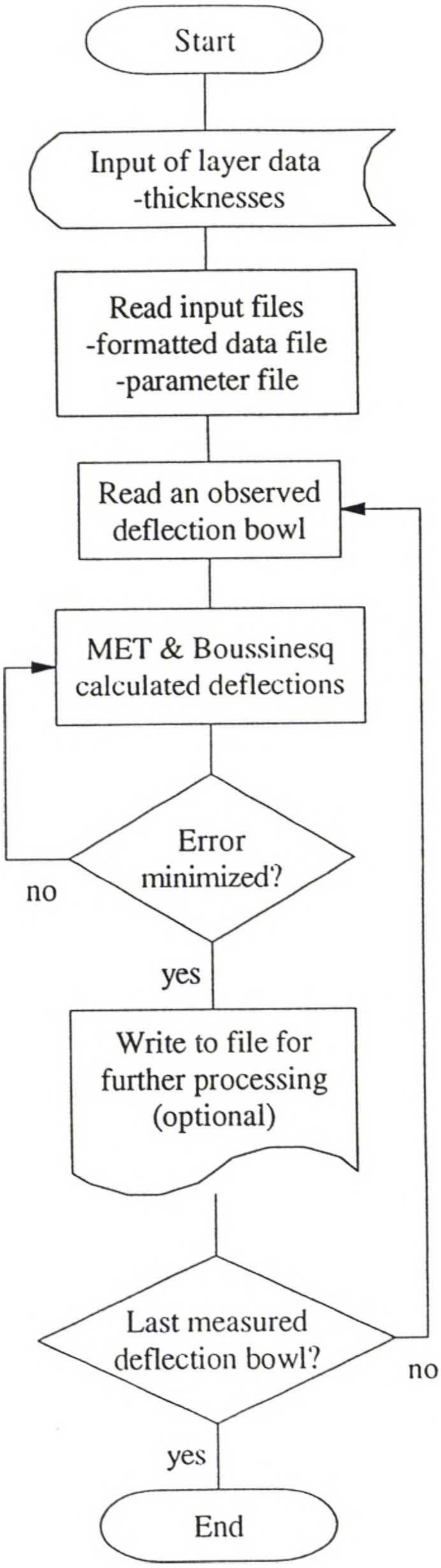


Figure 16. Simplified flow chart for Elmod-program [3].

where	h_e is	equivalent thickness of the layer
	n	correction factor
	h_i	original thickness of the layer
	E_i	modulus of the layer
	E_m	modulus of the underlying layer
	μ_i	Poisson's ratio of the layer
	μ_m	Poisson's ratio of the underlying layer

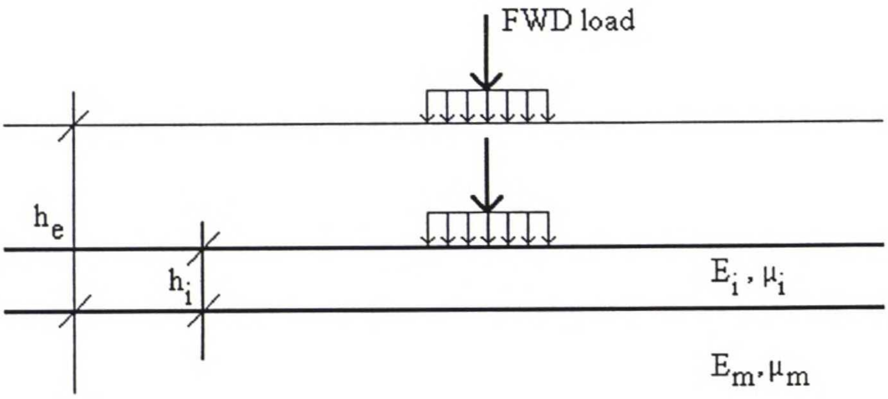


Figure 17. Method of equivalent thicknesses (MET) [14].

Poisson's ratio is taken to be μ=0.35 for all layers, and is therefore eliminated from the equation. The thickness of the equivalent structure with one modulus value E, having the same stiffness (EI) as the original structure, is calculated. Deflections of equivalent structure are computed with Boussinesq's equations. The measured deflections are compared to the computed ones, and iteration takes place to obtain the best fit between measured and calculated deflections.

The backcalculated subgrade modulus from Elmod is non-linear, taking into account the stiffening of the subgrade material with depth. The subgrade modulus is calculated from the following formula [3]:

$$E_{sg}=C_0*\left(\frac{\sigma_1}{\sigma'}\right)^n \tag{12}$$

where	E_{sg} is	subgrade modulus
	σ_1	major principal stress
	σ'	reference stress
	C_0, n	constants, $n < 0$

The maximum equal depth to the rigid layer is an optional user-supplied input to Elmod. The program calculates equivalent depth to the bedrock for each test point and makes a correction to the deflection bowl. The subgrade modulus is determined on the basis of the outer three sensors in Elmod.

5 DESCRIPTION OF TEST SECTIONS AND DATA COLLECTION PROCEDURES

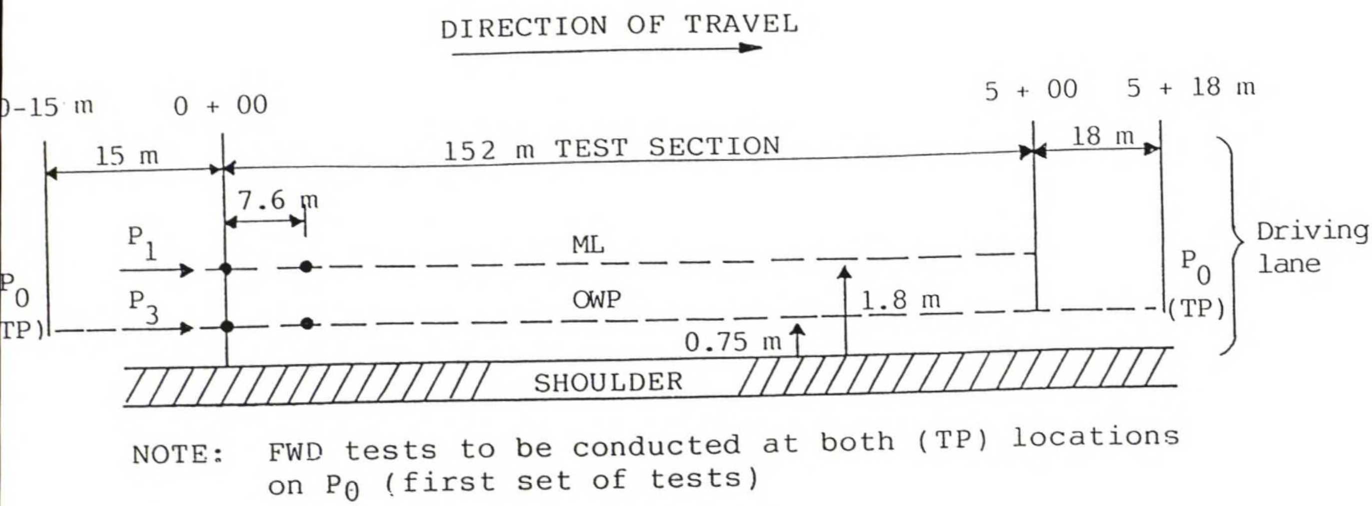
The Technical Research Centre of Finland (VTT) and the Finnish Road Administration (FinnRA) are collaborating with the U.S. Strategic Highway Research Program (SHRP) in the Long-Term Pavement Performance (LTPP) project. The Finnish LTPP-project includes 18 GPS-1 test sections and 25 GPS-6 test sections selected from in-service pavements. The structures of GPS-1 test sections consist of one asphalt layer on an unbound gravel base, and GPS-6 sections of two asphalt layers on an unbound gravel base. The length of each test section is 152 m [15].

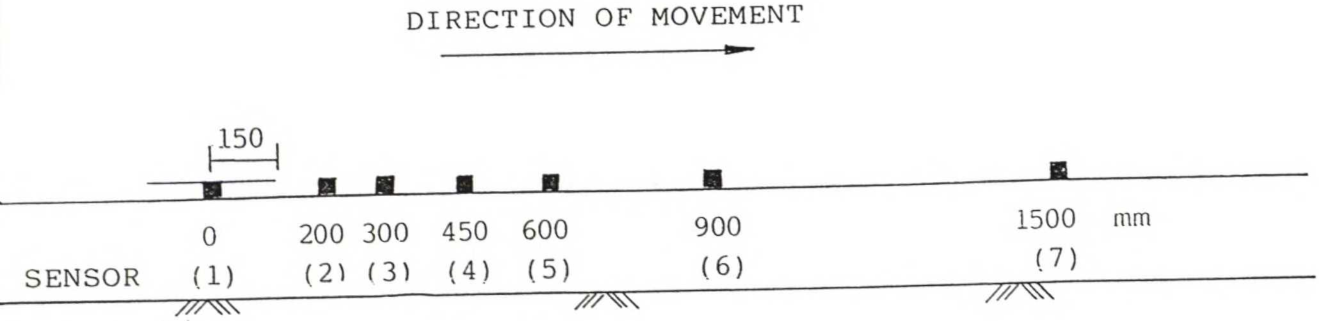
As part of the study, FWD measurements were carried out on the test sections during the summer and autumn of 1991-92. Test pits were made in order to determine layer thicknesses for each test section. One test pit for each test section was opened 18 m after the end of the section. The layer moduli were backcalculated from measured surface deflections using layer data from test pits as input to the backcalculation programs.

The data collection procedures were those described in the SHRP Operational field guidelines [15]. The FWD test plan, sensor configuration, and locations of drill holes for asphalt temperature measurements in the GPS-1 and GPS-6 test sections are presented in Figure 18 [15]. Measurements were carried out in both outer wheel path and midlane with 7.6 m spacing. The total number of test points was 42 on the 152 m long test section. In addition, measurements were made at two points outside the test section, one 15 m before, and one 18 m after the test section, at the point where the test pit was made.

The sensor spacing applied in the study was 0, 200, 300, 450, 600, 900, and 1500 mm. The asphalt temperature was normally recorded at one location at three depths: 25 mm below the surface, in the middle of the asphalt layer, and 25 mm above the bottom of the asphalt layer. The maximum depth at which the temperature was measured was 100 mm.

The measurements were carried out at four loading levels in order to determine the stress-sensitivity of paving materials. The target load was 27 kN at height one, 40 kN at height 2, 50 kN at height 3, and 71 kN at height 4. The same drop-height setting was used for all test sections with three drops at each of the four





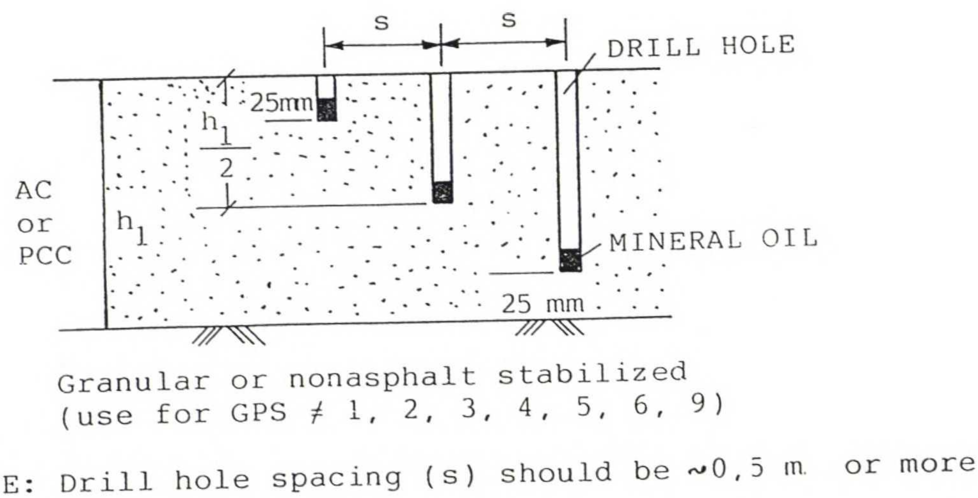


Figure 18. FWD test plan, sensor configuration and location of drill holes for asphalt temperature measurements for GPS-1 and GPS-6 test sections [15].

heights after three seating drops at height three. The maximum deflection at each sensor and peak load, excluding seating drops, was recorded.

One test pit per test section was opened 18 m after the end of the section, following the SHRP Operational field guidelines [15]. Nine samples of asphalt layer were cored in order to determine the asphalt layer thickness and obtain samples for laboratory testing. Layer thicknesses were recorded and samples for laboratory testing were exctracted. The in-situ degree of compaction of each layer was measured with a Troxler device.

6 INPUT TO BACKCALCULATION PROGRAMS

The layer moduli from deflection data from the test sections were backcalculated with two programs, Modulus and Elmod. The SHRP-LTPP guidelines for the backcalculation procedure using the Modulus-program were followed [16].

The layer thicknesses observed from test pits were used as input. An average thickness of nine samples was used for asphalt layer thickness. All bituminous layers were combined into one layer. The thickness of the asphalt layer varied between 46-147 mm with an average of 77 mm for GPS-1 sections and between 61-207 mm with an average of 120 mm for GPS-6 sections (Figures 19 and 20 [17]).

Unbound layers with similar properties were combined to make a four-layer structure. The total thickness of the unbound layers varied between 510-1600 mm, with an average of 966 mm for GPS-1 sections, and between 540-1620 mm with an average of 1028 mm for GPS-6 sections (Figures 21 and 22 [17]). A thin base layer (100 - 150 mm) was combined with the underlying layer, if the resulting moduli values turned out to be exceptionally high. The depth to a rigid layer was determined by the program. Poisson's ratio of μ=0.35 was used for all layers.

Considerably wide bounds were given for layer moduli using the Modulus-program because of rather large variation within the section. Since no such knowledge as asphalt binder and void content or aggregate grading were present, bounds for asphalt layer modulus were simply given reasonably wide. In case the thickness of the asphalt layer was less than half the radius of the loading plate (<75 mm), its modulus was fixed by giving an estimate of the modulus as both lower and upper bound.

For the base and subbase layers, bounds for moduli were given on the basis of the material type derived from the test pit. The subgrade modulus was estimated using the following equations [18]:

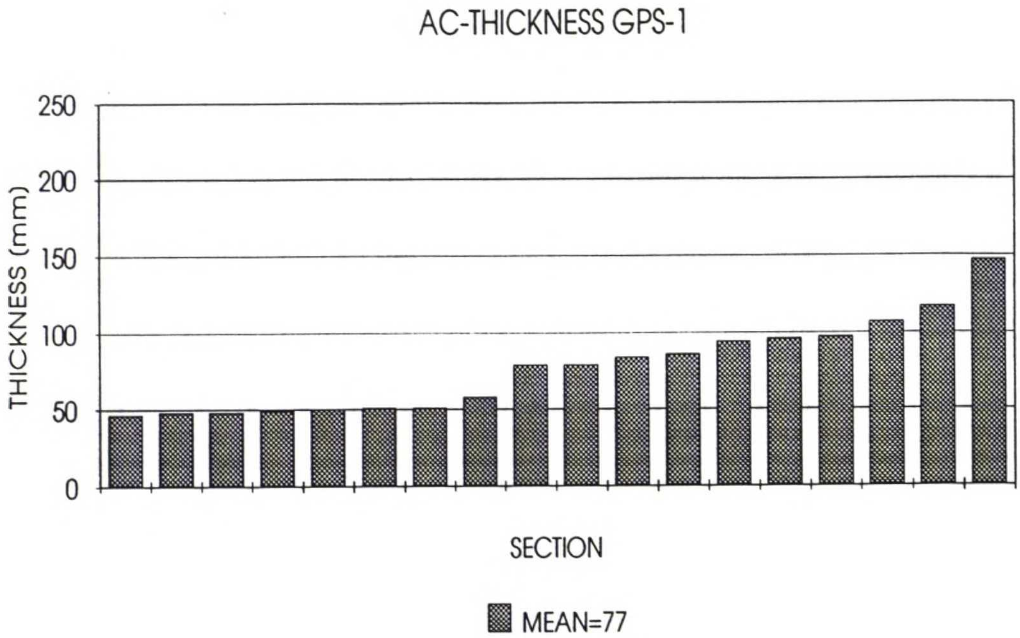


Figure 19. Distribution of asphalt layer thicknesses for GPS-1 test sections [17].

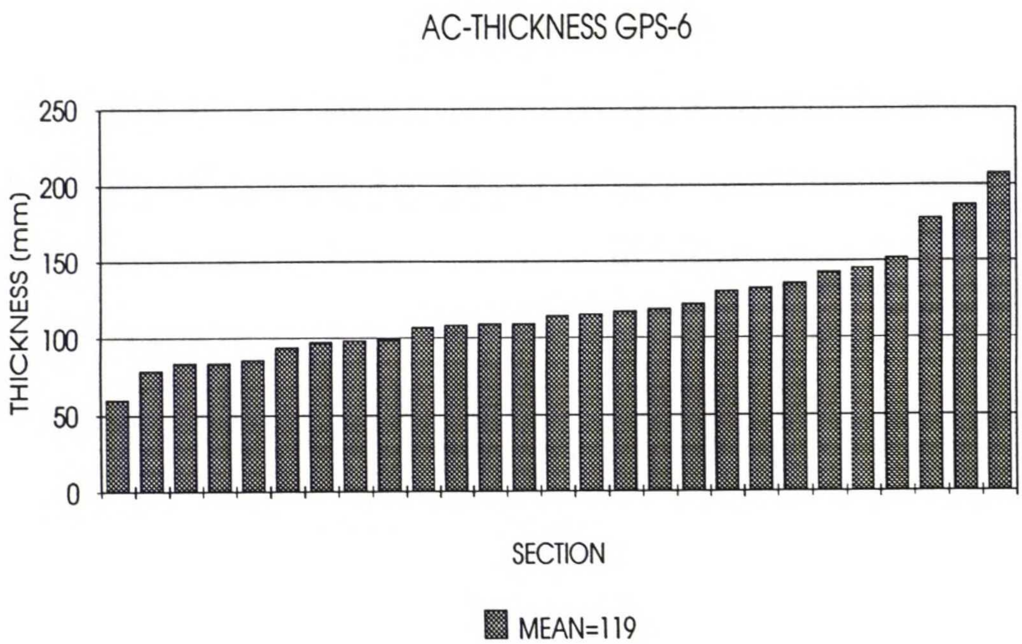


Figure 20. Distribution of asphalt layer thicknesses for GPS-6 test sections [17].

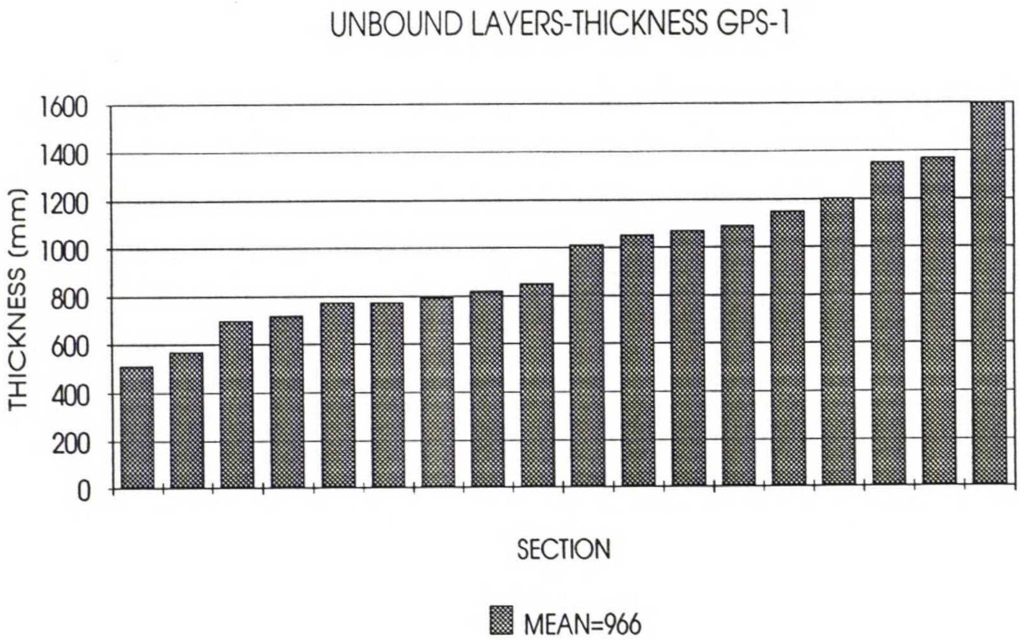


Figure 21. Distribution of total thickness of unbound layers for GPS-1 test sections [17].

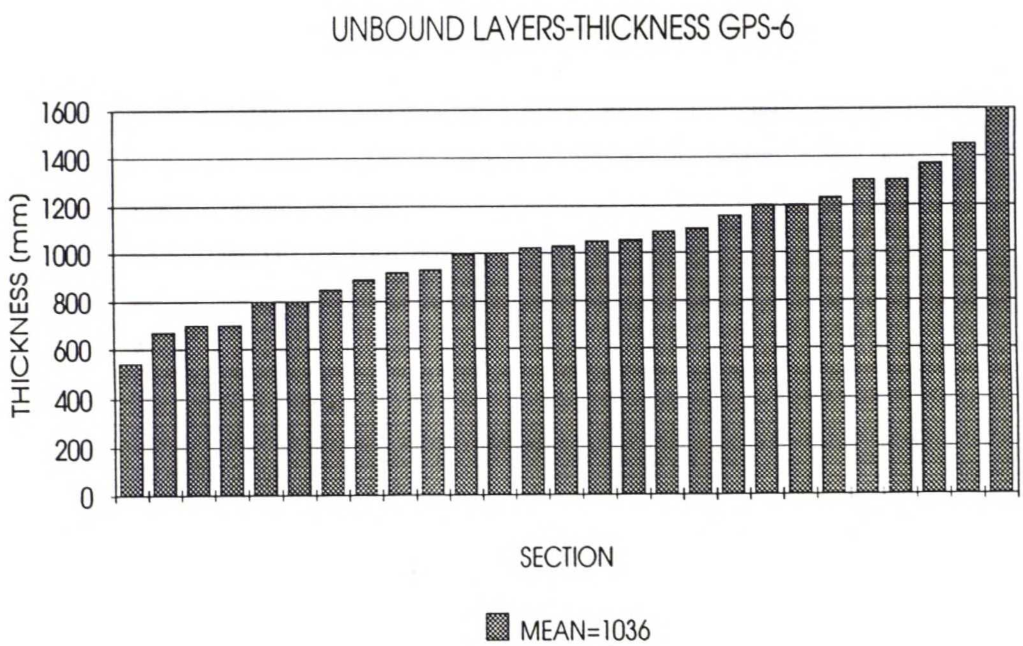


Figure 22. Distribution of total thickness of unbound layers for GPS-6 test sections [17].

$$E_{sg}=-3.65435+24.398*(\frac{P}{D_3}) \tag{13}$$

$$E_{sg}=20308*\frac{P}{D_r*r} \tag{14}$$

where	E_{sg} is	subgrade modulus, MPa
	P	load, kPa
	D_3	surface deflection at 914 mm (3 ft), µm
	D_r	surface deflection at distance r, µm
	r	deflector distance from loading plate, mm

Since the backcalculated subgrade moduli were found to be systematically lower than estimates from equations (13) and (14), input was revised.

Layer thicknesses including maximum depth to rigid bottom are the only user-supplied input to the Elmod-program. The same layer thicknesses were used with both programs. The stiff-layer calculation option in Elmod was only used for a few test sections, because using it would, in many cases, only increase error in the calculated deflections, but not affect the backcalculated moduli as much. In Elmod, also a fixed value for the asphalt layer can be given by the user, and this was done in the case of thin asphalt layers. The Poisson ratio of µ=0.35 is assumed for all layers within the program [3].

The backcalculated asphalt moduli values from both programs were corrected to a reference temperature of +21 °C (+70 °F) according to the procedure presented in the AASHTO Design Guide [19].

7 MATERIAL MODULI AT STANDARD WHEEL LOAD

7.1 COMPARISON OF MODULI FROM THE TWO PROGRAMS

The backcalculated layer moduli at 50 kN wheel load, equivalent to Finnish standard axle load of 100 kN, are compared in Figures 23 to 26. In the figures, one data point represents results from one test section, which is the average of the 42 test points.

From Figure 23 it is seen, that the asphalt layer moduli from both programs are reasonable for bituminous material from a dynamic test. Values in Figure 23 are corrected to a reference temperature of +21 °C (70 °F) [19]. The variation in asphalt modulus between test sections results from differences in pavement condition, age, etc. For values up to 7000 MPa, which are expected for the asphalt layer modulus from a dynamic test, from all except three of the test sections, higher asphalt modulus values are obtained from Modulus than from Elmod.

Within the normal range for layer moduli, that is below 500 MPa for the base and subbase, and below 200 MPa for subgrade (Figures 24 through 26), Elmod gives higher values than Modulus. This may be due to the bottom-to-top approach used in Elmod; a solution of layer moduli starts from the subgrade upwards. The subgrade modulus is assigned a value based on the outer three deflections. According to reference [12], giving a large emphasis on outer sensor readings in the deflection matching procedure causes an overestimation of subgrade modulus. Similarly, the modulus of the upper (asphalt) layer is underestimated.

A comparison of the Modulus- and Elmod-programs was made with deflection data simulated with the linear elastic multi-layer program [20] (BISAR). It was found that the backcalculated subgrade modulus values from the Elmod-program were generally 20% greater compared to the values used in the deflection bowl simulation.

A linear correlation between the backcalculated asphalt modulus from the two programs was developed:

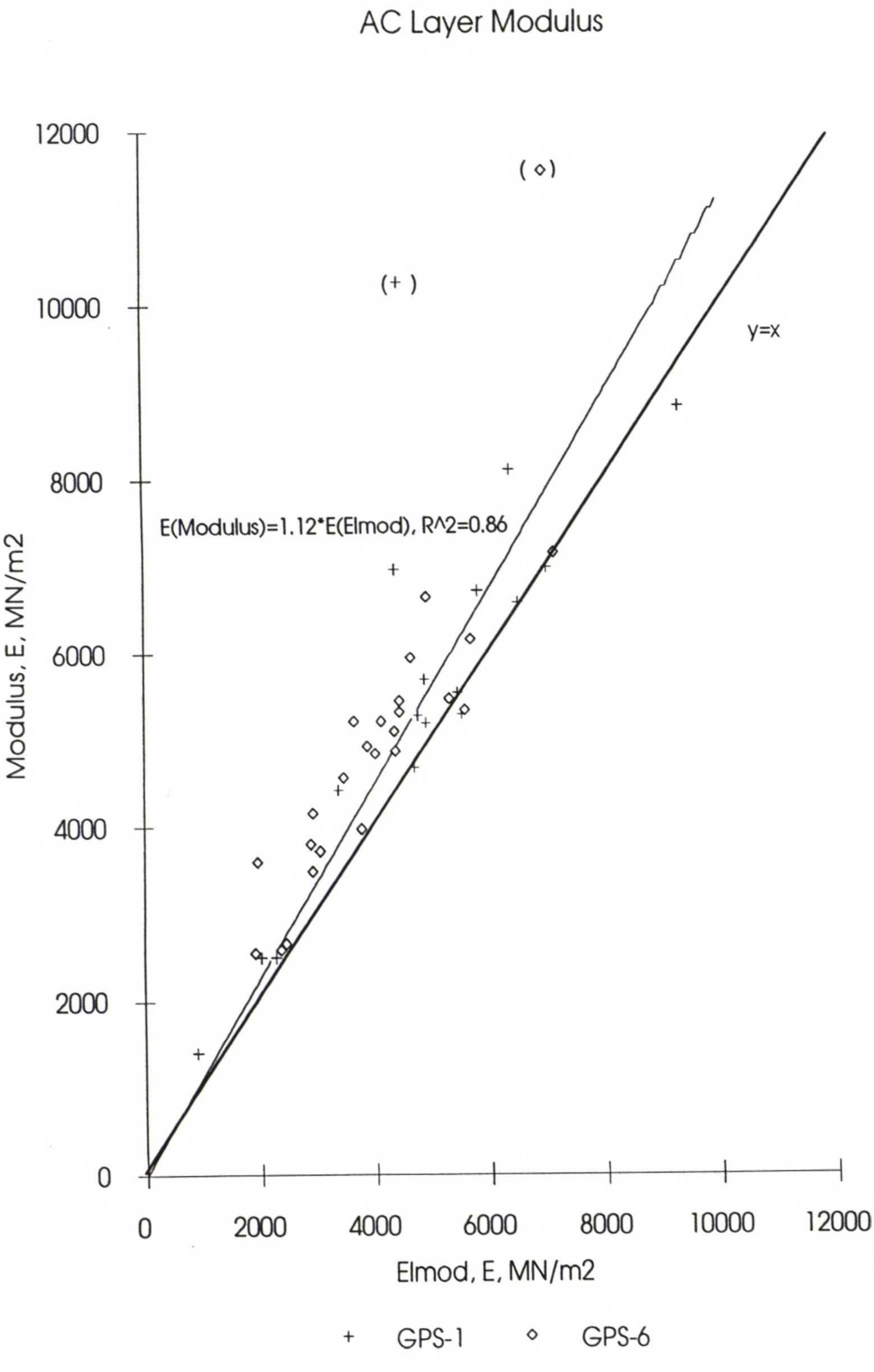


Figure 23. Finnish SHRP-LTPP study. Comparison of backcalculated AC modulus from Modulus- and Elmod-programs.

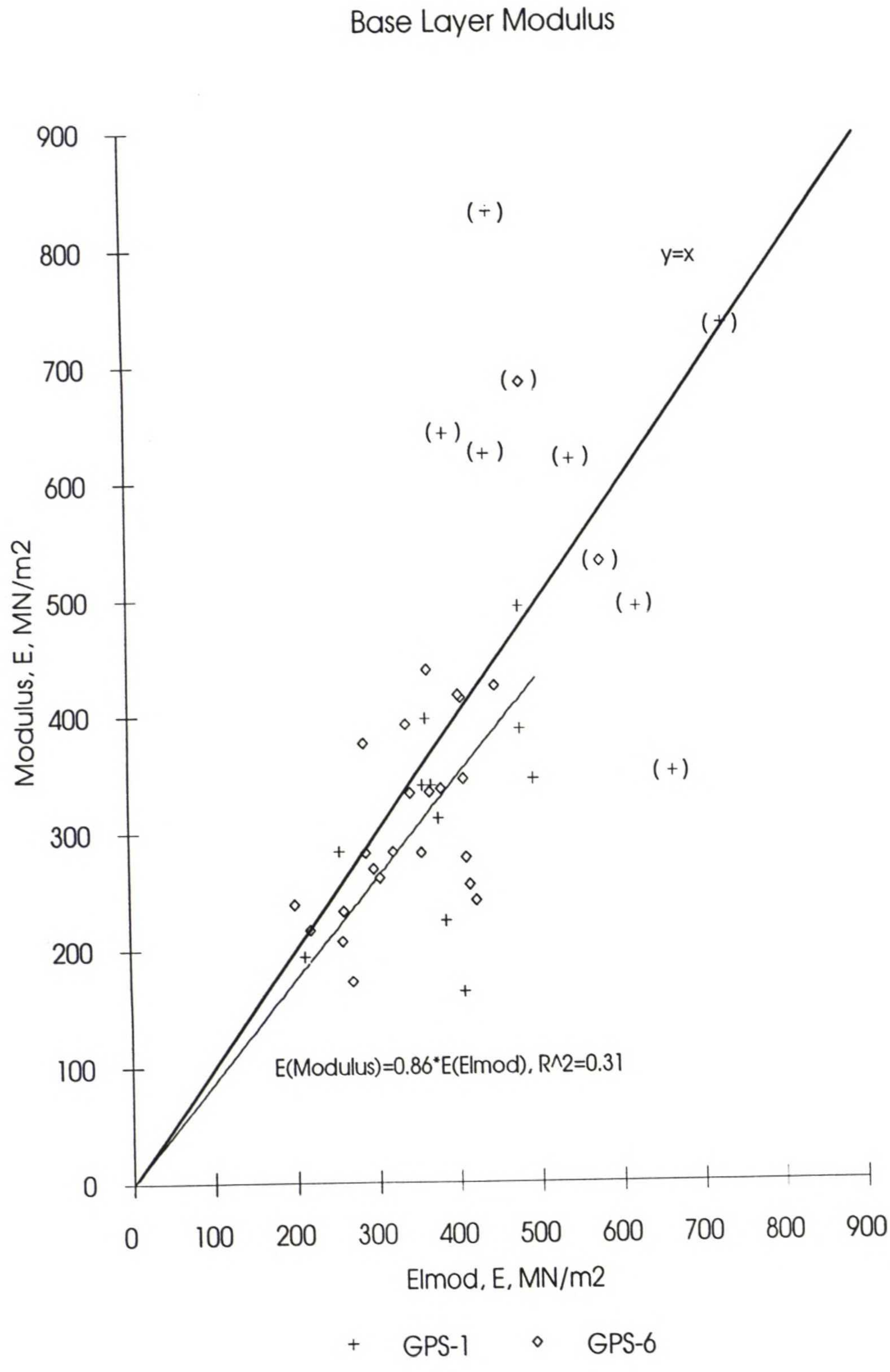


Figure 24. Finnish SHRP-LTPP study. Comparison of backcalculated base layer modulus from Modulus- and Elmod-programs.

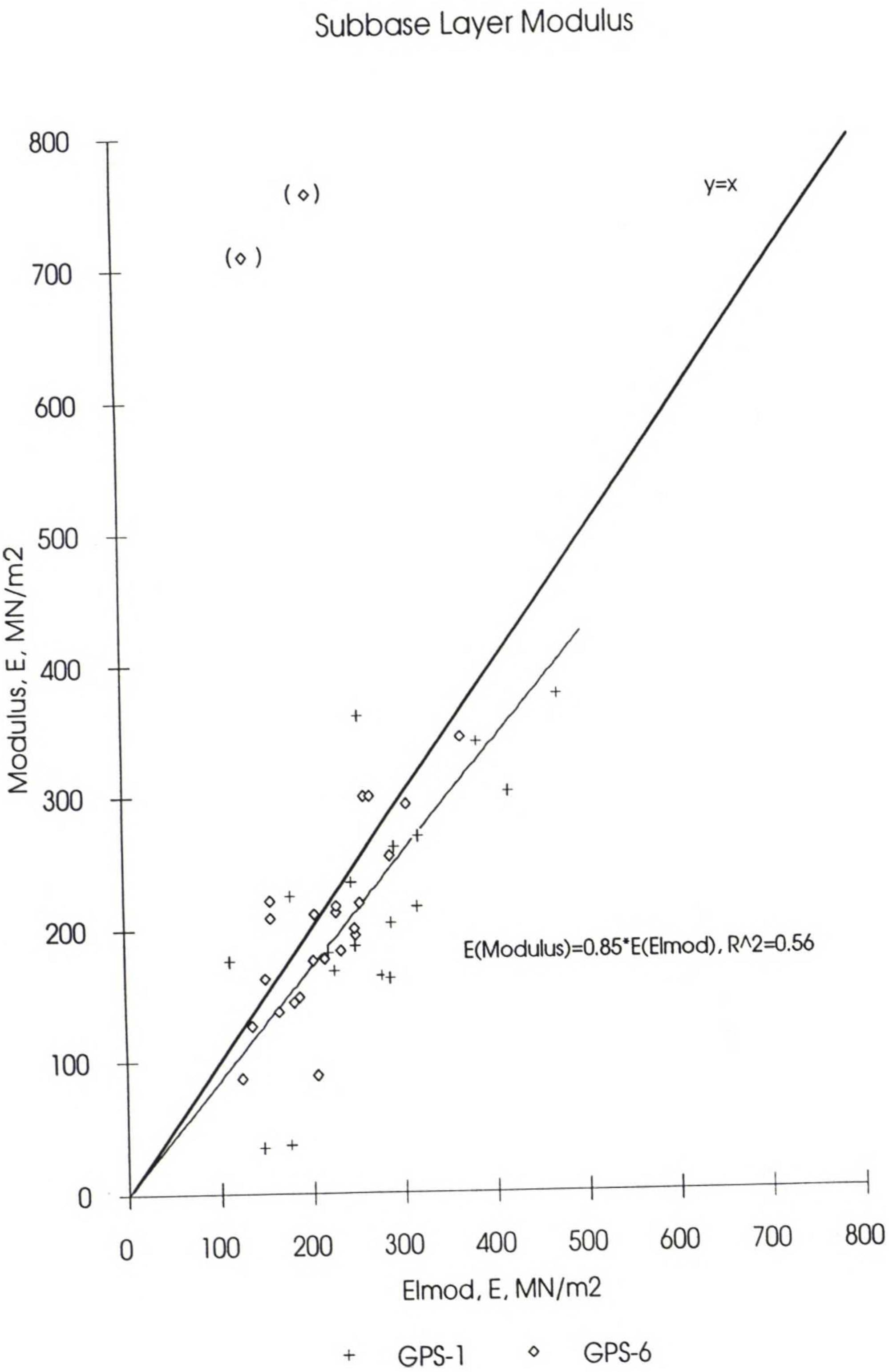


Figure 25. Finnish SHRP-LTPP study. Comparison of backcalculated subbase layer modulus from Modulus- and Elmod-programs.

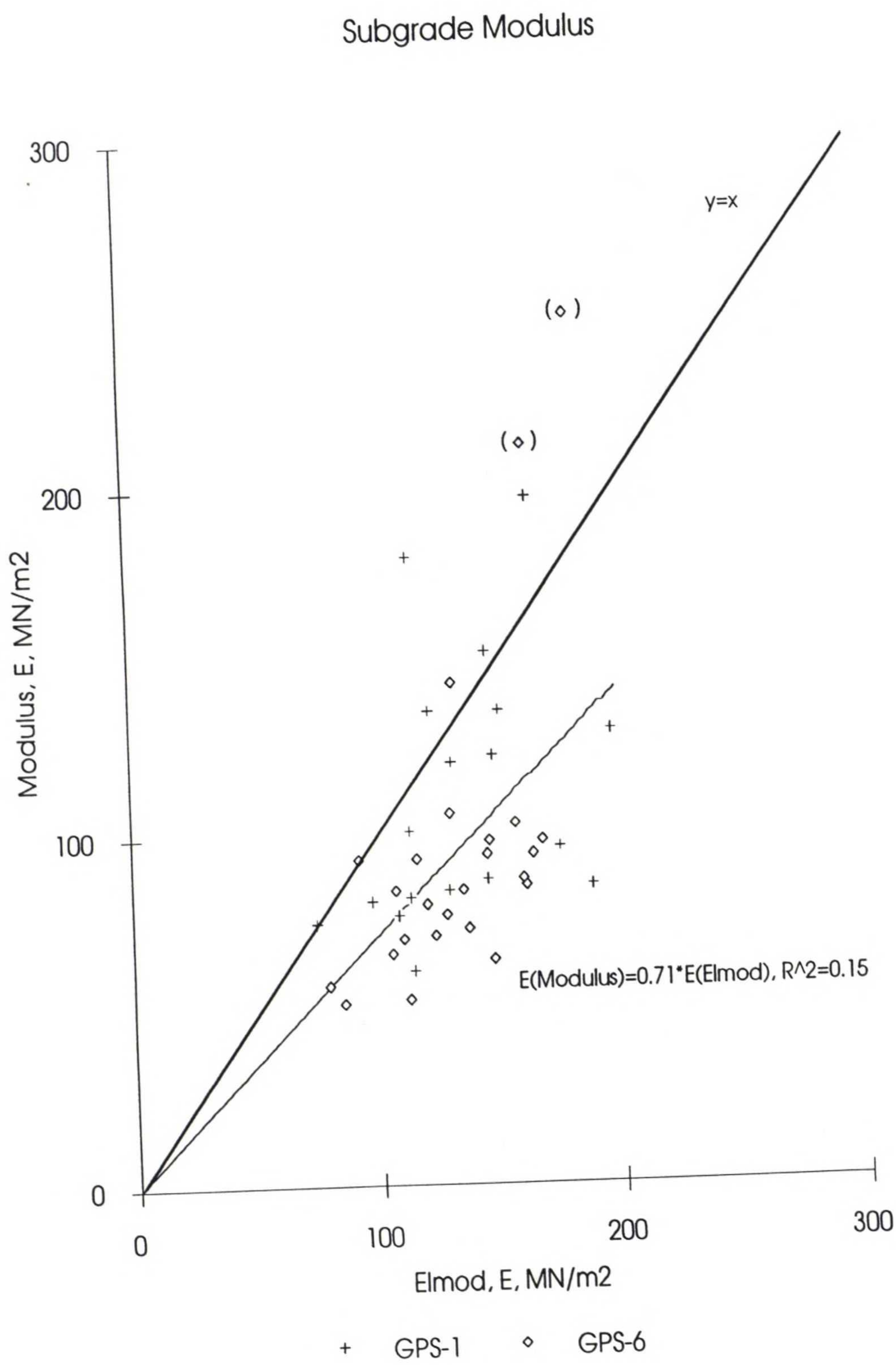


Figure 26. Finnish SHRP-LTPP study. Comparison of backcalculated subgrade modulus from Modulus- and Elmod-programs.

$$E_{Modulus}=1.12*E_{Elmod},\ R^2=0.86 \tag{15}$$

where $E_{Modulus}$ is the backcalculated layer modulus from the Modulus-program

E_{Elmod} the backcalculated layer modulus from the Elmod-program

This relationship is not meant for transforming results from one program to another, but rather to give an idea of how the backcalculation results differ between the programs. Two odd points with a modulus value above 10 000 MPa were left out of the correlation.

Similar relationships between the backcalculated unbound layer moduli from the two programs were developed for

base:

$$E_{Modulus}=0.86*E_{Elmod},\ R^2=0.31 \tag{16}$$

subbase:

$$E_{Modulus}=0.85*E_{Elmod},\ R^2=0.56 \tag{17}$$

subgrade:

$$E_{Modulus}=0.71*E_{Elmod},\ R^2=0.15 \tag{18}$$

Again, some odd points above 500 MPa for base and subbase, and 200 MPa for subgrade were left out of the correlation. Correlations (R^2) in equations (16)-(18) are rather poor, which indicates some variability between moduli values calculated with the programs. It is seen that the greatest differences between the programs occur with the backcalculated subgrade modulus. This is one of the most important input parameters to mechanistic design procedures. Therefore, it is essential to know whether the backcalculated subgrade modulus values are realistic, or obviously too high or low.

The falling weight deflectometer causes a dynamic loading to the pavement structure. Both backcalculation programs used in this study calculate deflections from a static load equal in magnitude to the peak dynamic load. Deflection from a static load is greater than that from a dynamic load. This is likely to cause overestimation in the calculated layer moduli.

The relation between the base and subbase modulus (E_2/E_3), is either calculated or user-defined constant in Elmod. In the first case, the following relationship is used in conjunction with the method of equivalent thicknesses (MET) to calculate the ratio E_2/E_3 [3]:

$$\frac{E_g}{E_s} = 0.2 * h_g^{0.45} \tag{19}$$

where	E_g is	granular layer modulus
	E_s	subgrade modulus
	h_g	granular layer thickness

This means that in program output, the base layer will always be assigned a higher modulus value than the subbase layer. Also, the ratio of the base to subbase modulus will be the same in every test point within a section. This may well be true for certain structures, but, for example, an old base layer in a reconstructed pavement may have a higher modulus than a layer of finer material placed on it. This can be seen from the results of the Modulus-program, where a higher value is assigned for the subbase than the base modulus in some cases. Unreasonably high layer modulus values may also be due to an unknown variation in layer thickness within the test section; the thickness of a layer varies from the value observed from the test pit.

7.2 ERROR IN CALCULATED DEFLECTIONS

Error between measured and calculated deflections is a measure by which it is judged whether reasonable backcalculated layer moduli are obtained. Error is given with the precision of 1 percent in Elmod, whereas it is given with the precision of 1/100 of 1 percent in Modulus.

The average error per sensor of the 42 test points at a test section was calculated and the error distribution of all test sections is shown in Figure 27 for the Modulus-program and in Figure 28 for the Elmod-program.

From the figures it is seen that for most of the test sections, error is less than 2% in the Modulus calculations except for some odd points. Error in the Elmod calculations is generally of a higher level. With both programs, the greatest errors occur, when the modulus of bituminous layers is not calculated, but fixed, i.e. it is assigned a constant value. As described in chapter 6, this is to be done when the thickness of the bituminous layer is less than half the radius of the loading plate (75 mm).

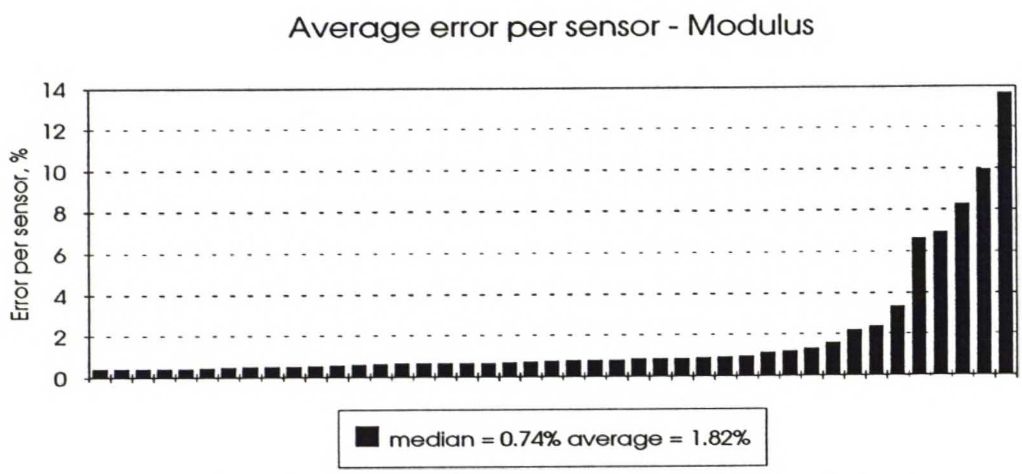


Figure 27. Finnish SHRP-LTPP study. Average error per sensor. Modulus backcalculation program.

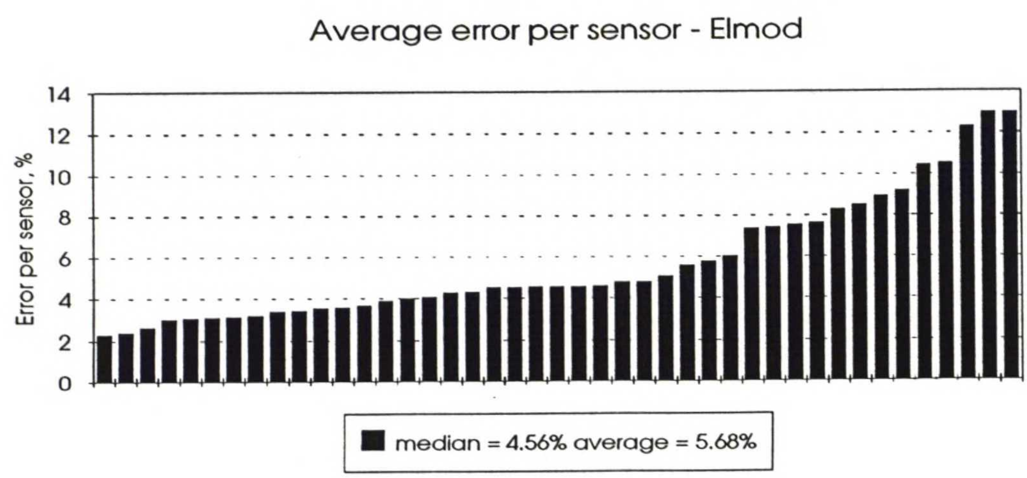


Figure 28. Finnish SHRP-LTPP study. Average error per sensor. Elmod backcalculation program.

The average error in all test sections from Modulus is 1.82% and from Elmod 5.68%. A few large errors increase the average, therefore the median is preferred in describing the distribution. For Modulus the median error is 0.74% and 4.56% from Elmod. It is seen that error is about five times as large in Elmod than in Modulus. The smallest value for error in Elmod is 2.26%, which is still above the acceptable level of 2%, as set out in the SHRP's backcalculation procedure [16]. It may be questioned, whether such criteria should even be set for Elmod involving a totally different calculation method. As noted above, error is expressed in different orders of magnitude in the Modulus and Elmod programs, and is therefore not directly compareable.

It is seen that in Modulus, theoretical fit between measured and calculated deflections is sought for, allowing high modulus values in the output, if they seem theoretically correct. Modulus values within reasonable limits, but perhaps incorrect, are obtained with Elmod. It is worth noting here, as will be seen in chapter 9, that this systematic error in the backcalculation system is somewhat outbalanced in the forward-calculation of critical strains, because method of equivalent thicknesses is used in both directions [3].

7.3 VARIANCE IN BACKCALCULATED LAYER MODULI

The coefficient of variation (CV) of modulus describes the variation in layer material. It is defined as the ratio of sample standard deviation (stds) to the average (avg) of the 42 test points:

$$CV=\frac{stds}{avg} \tag{20}$$

The average and median values of variation coefficient for the 43 test sections are presented in Figures 29 and 30. The coefficient of variation in the asphalt and subgrade modulus turned out to be the same or close to same for both programs.

The coefficient of variation in the base and subbase moduli from Modulus is twice as large as the coefficient of variation from Elmod. This is concluded to indicate that theoretical fit of deflections at each test point is found with Modulus, therefore yielding a unique set of layer moduli for each test point. Rather large within-section variation revealed by the relatively high variation coefficient is the outcome from this approach. Also, the variation coefficient for the base and subbase moduli from Elmod are equal. This, in turn, is owing to the fixed relation of the base to subbase modulus in Elmod. Since the relation of the base to

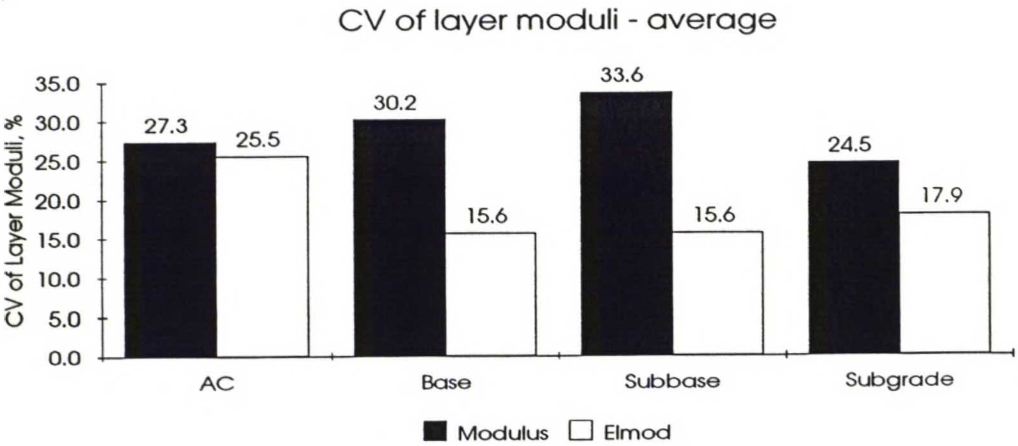


Figure 29. Finnish SHRP-LTPP study. Average coefficient of variation (CV) of layer moduli.

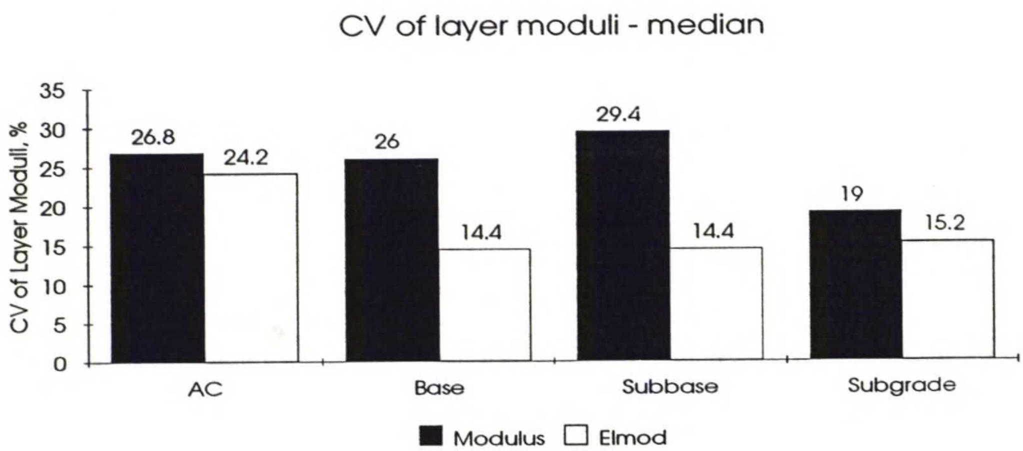


Figure 30. Finnish SHRP-LTPP study. Median coefficient of variation (CV) of layer moduli.

subbase modulus has to be equal at all test points within each run of the program, the variations in both layers will necessarily be equal.

The backcalculated asphalt layer and subgrade moduli are, according to a widely accepted viewpoint, more reliable than the backcalculated unbound granular base and subbase moduli. Based on the results of this study, and other experience in backcalculation analysis, it is this author's opinion, that the backcalculated unbound base and subbase layer moduli should be used with caution, and that Modulus is more suitable for determining pavement layer and subgrade moduli than Elmod.

8 INFLUENCE OF STRESS LEVEL ON LAYER MODULI

FWD testing was carried out at four different loading levels in order to study the stress-sensitivity of paving materials. Layer moduli for each loading level were determined as a four-layer solution with the Modulus- and Elmod-programs. Determining input to the programs for drop height three is described in chapter 6. The same input was used for the backcalculation of moduli at other loading levels. The moduli bounds were altered between different runs of the Modulus-program when necessary.

The plot of moduli versus load level for each layer is shown in Figures 31 to 34 for Modulus, and Figures 35 to 38 for Elmod. The values in Figures 31 and 35 are corrected to a reference temperature of +21 °C (70 °F) [19]. From the Figures it seems evident that loading level has the greatest effect on base course modulus. On the other hand, some of the moduli values seem unreasonably high. This may be due to linear analysis of non-linear materials [9] and static analysis of a dynamic phenomena, as described in chapter 7.1.

The backcalculated asphalt modulus seems to show stress-dependency with both programs. Elmod shows greater stress-dependency than Modulus. The average increase in asphalt modulus between the lowest and highest loading level is 23% with Elmod and 12% with Modulus. Furthermore, except for two test sections, the backcalculated asphalt modulus from Elmod calculations increases with increasing loading level, whereas the asphalt modulus obtained from Modulus calculations shows both an increase and decrease with increasing loading level, as can be seen from Figures 31 and 35.

Parker [8] encountered this phenomenon in his studies concerning the stress-dependency of materials using Elmod as a backcalculation program. He found no correlation between laboratory and field tests. Factors other than loading level, such as the linear elastic and static analysis approach, may cause an increase or decrease in the backcalculated asphalt layer modulus. This does not necessarily indicate actual non-linear behaviour of the bituminous material. However, asphalt concrete is a combination of granular material, which is known to be stress-dependent, and bitumen.

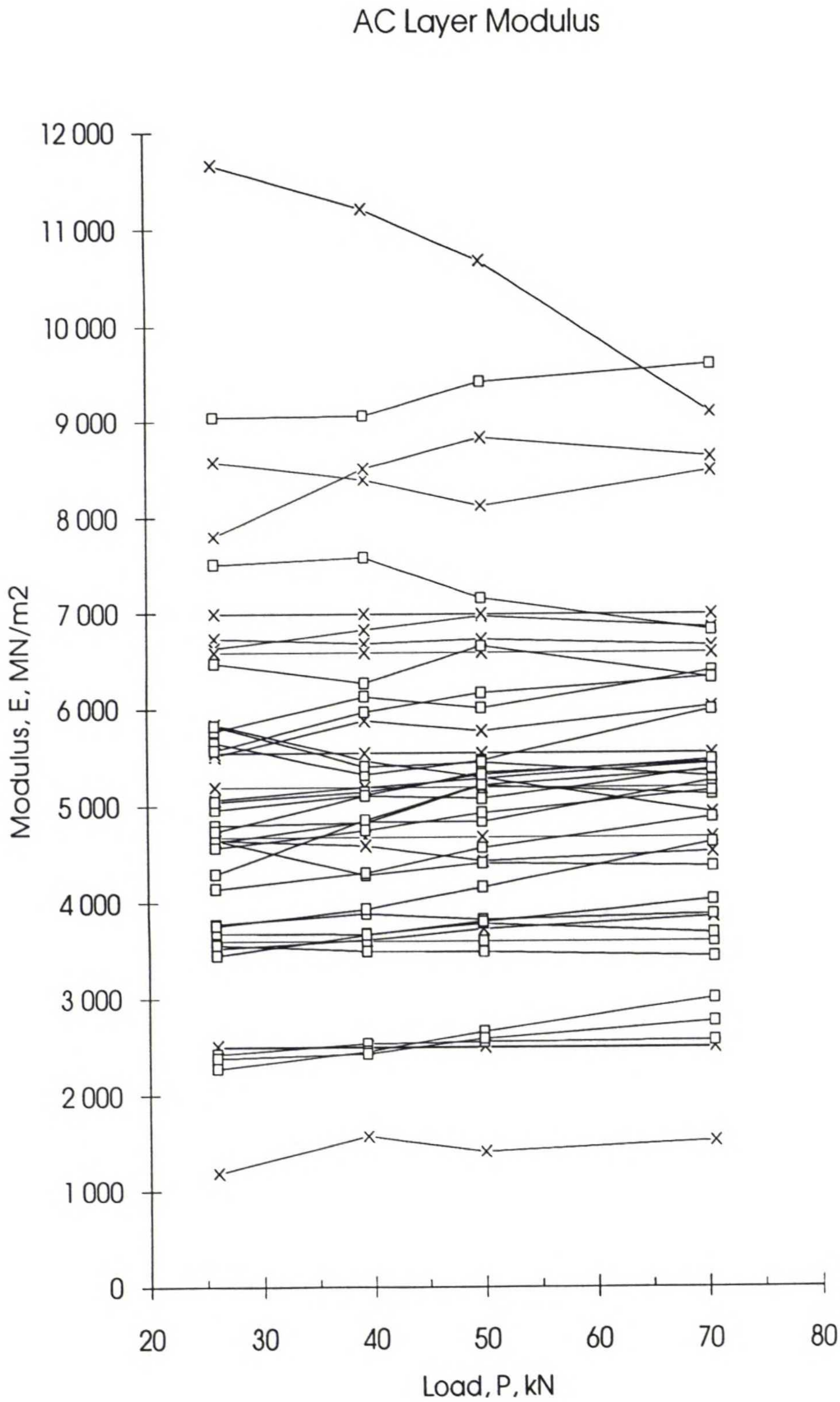


Figure 31. Finnish SHRP-LTPP study. Stress-dependency of backcalculated asphalt layer modulus. Modulus-program.

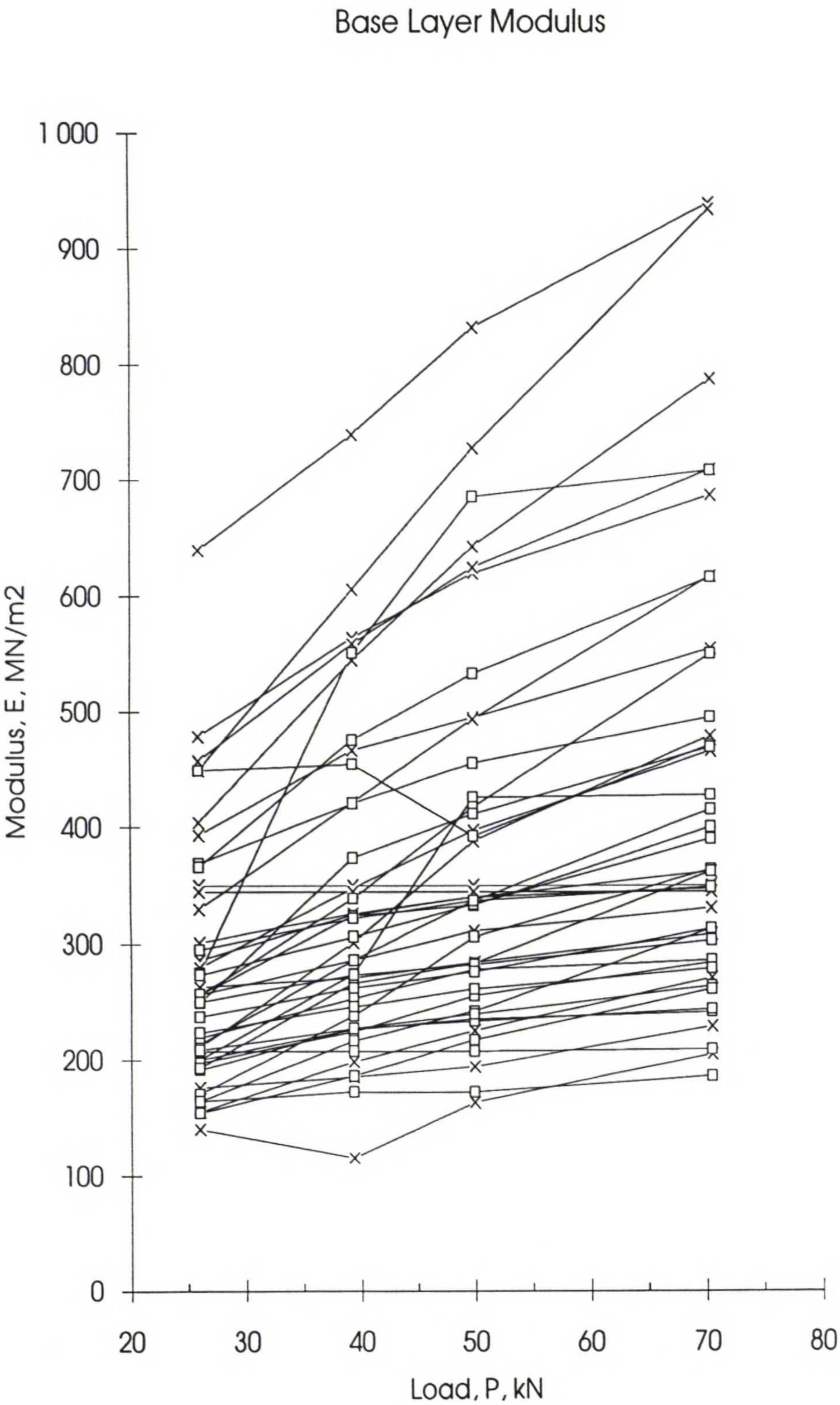


Figure 32. Finnish SHRP-LTPP study. Stress-dependency of backcalculated base course modulus. Modulus-program.

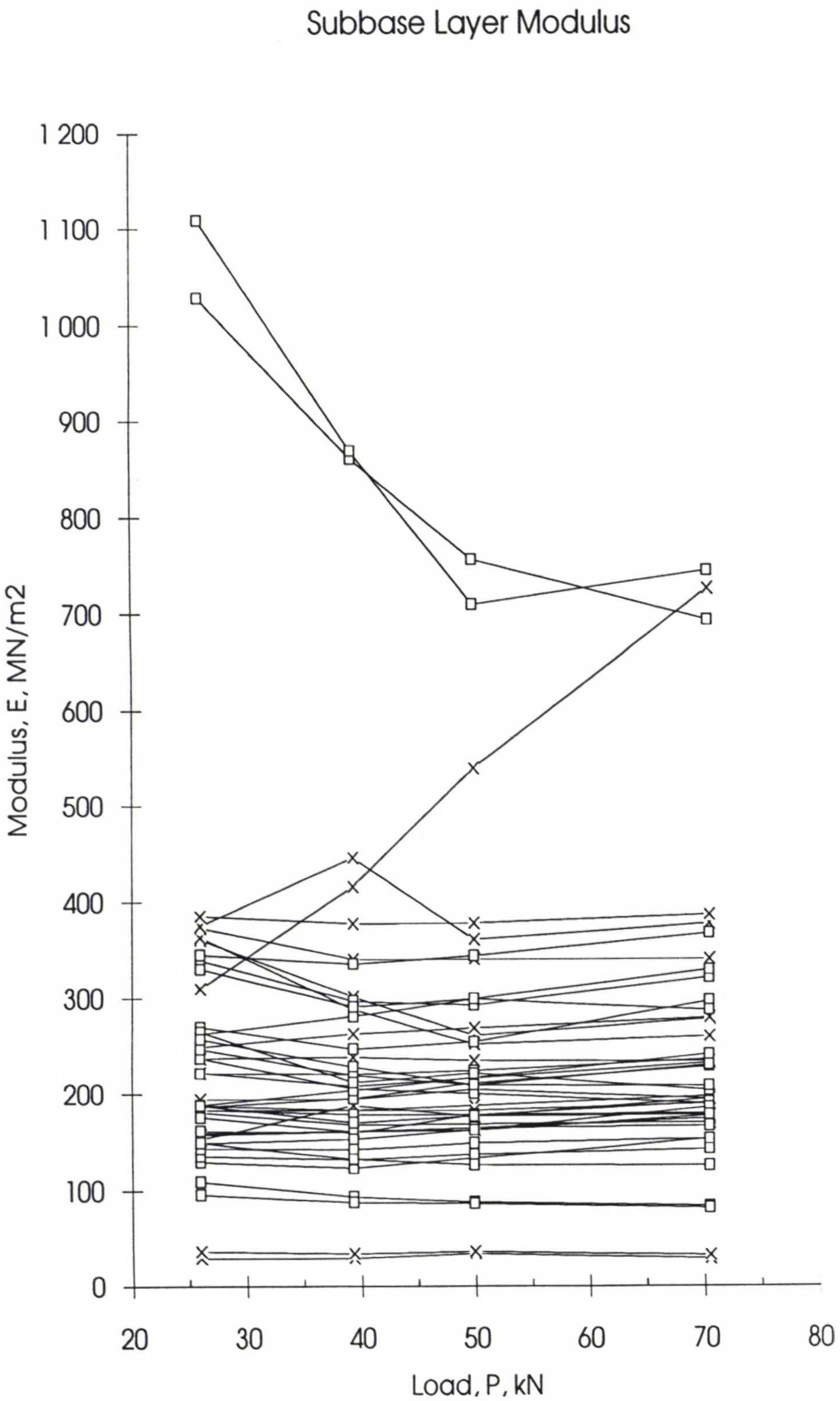


Figure 33. Finnish SHRP-LTPP study. Stress-dependency of backcalculated subbase course modulus. Modulus-program.

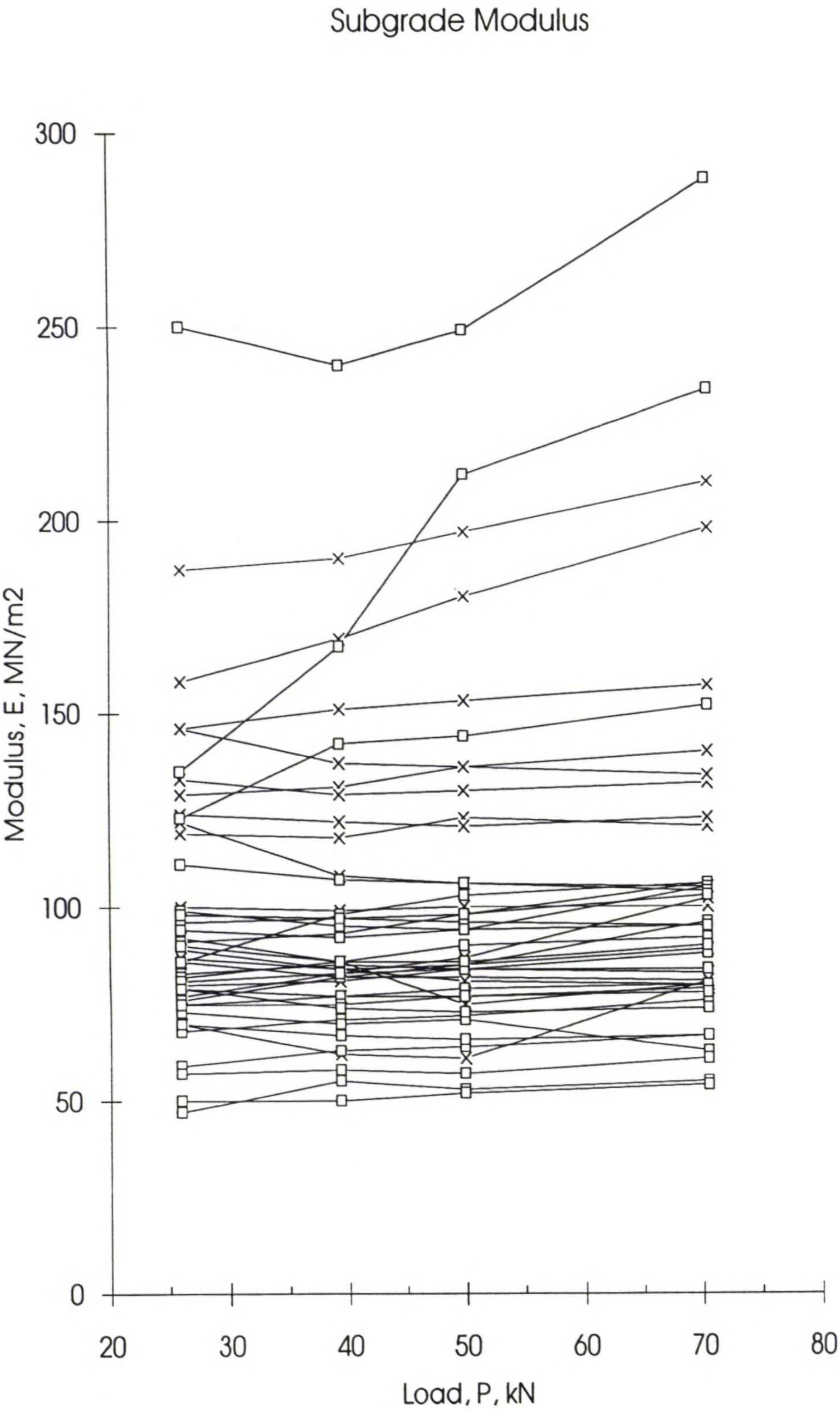


Figure 34. Finnish SHRP-LTPP program. Stress-dependency of backcalculated subgrade modulus. Modulus-program.

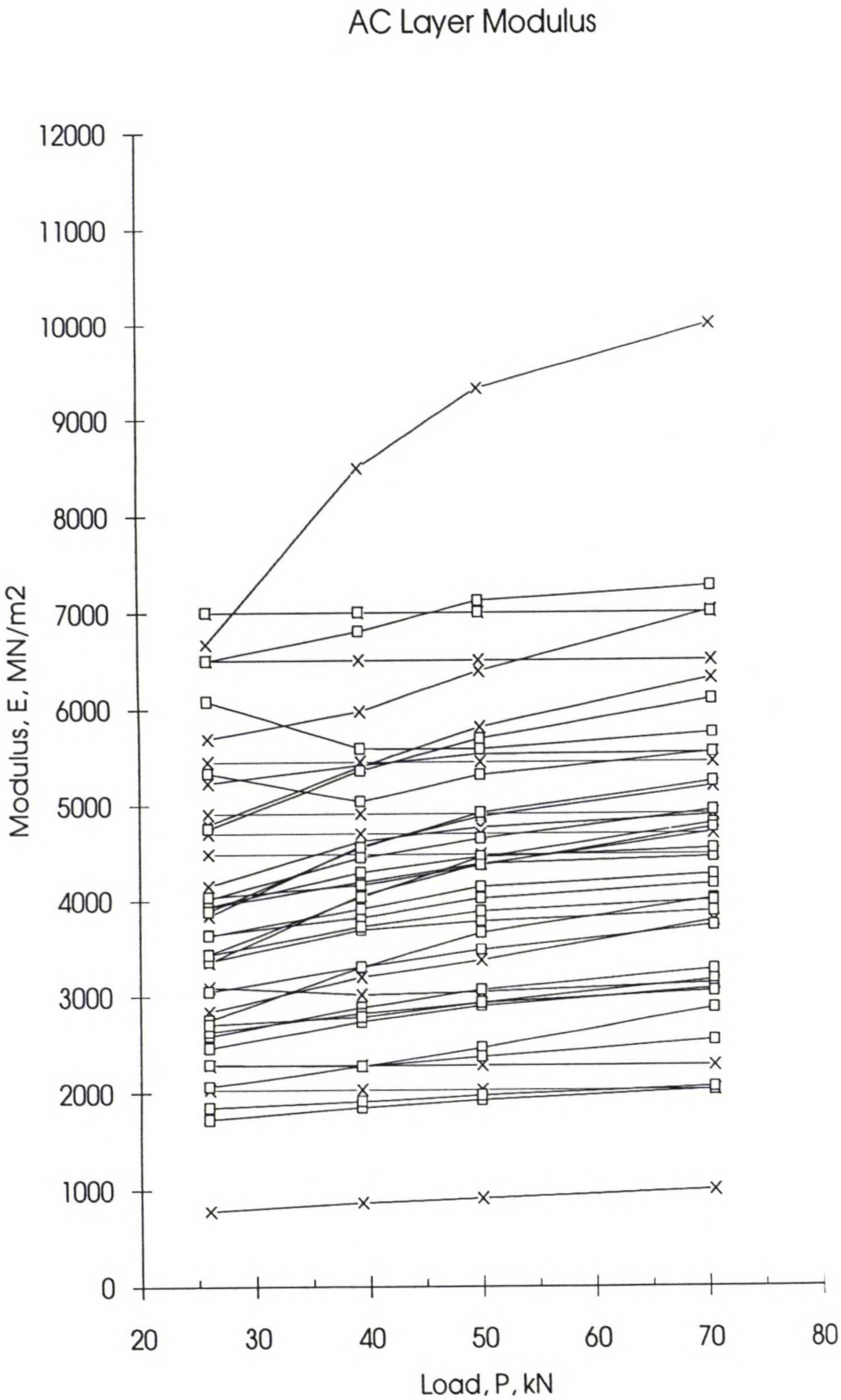


Figure 35. Finnish SHRP-LTPP study. Stress-dependency of backcalculated asphalt layer modulus. Elmod-program.

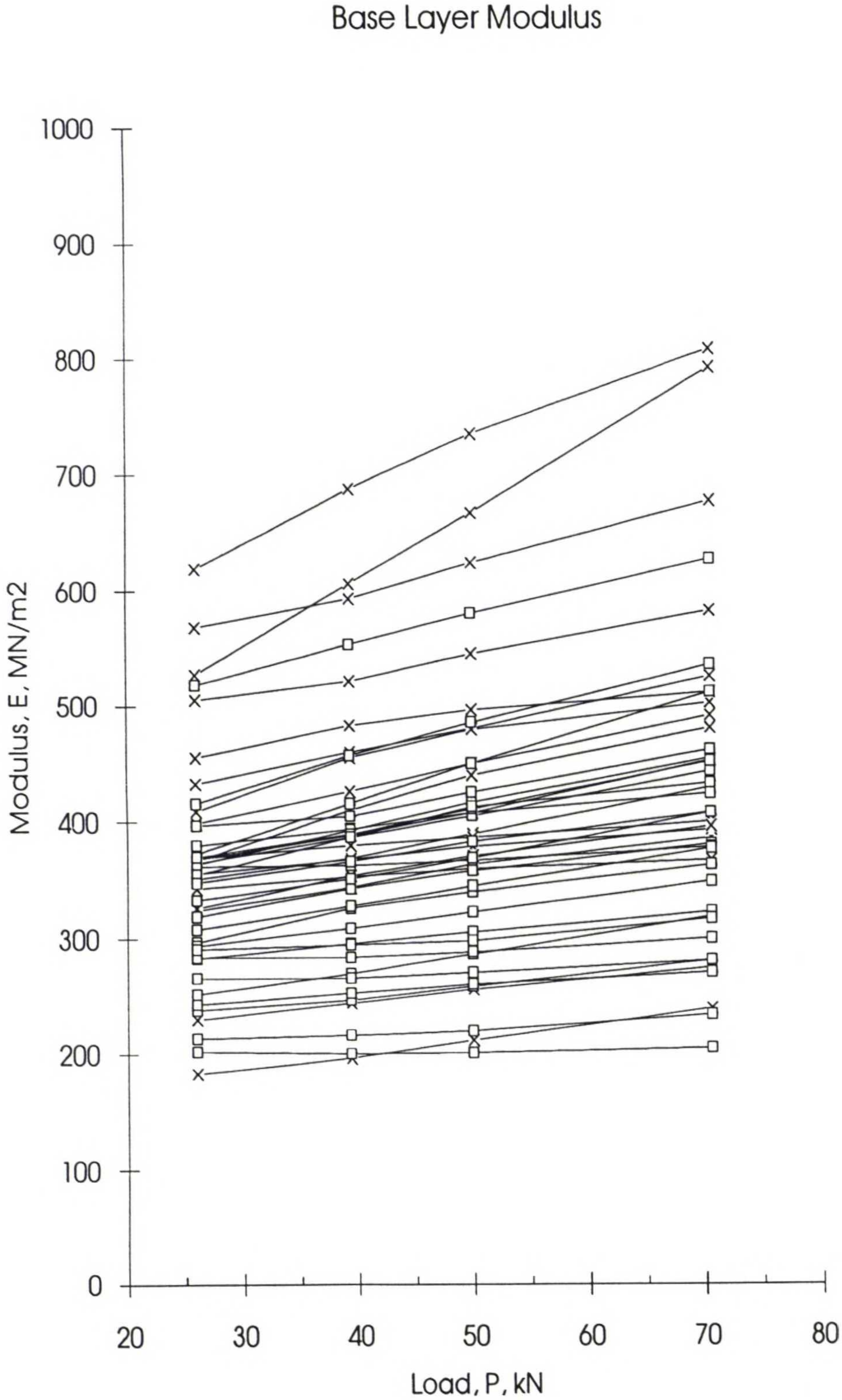


Figure 36. Finnish SHRP-LTPP study. Stress-dependency of backcalculated base course modulus. Elmod-program.

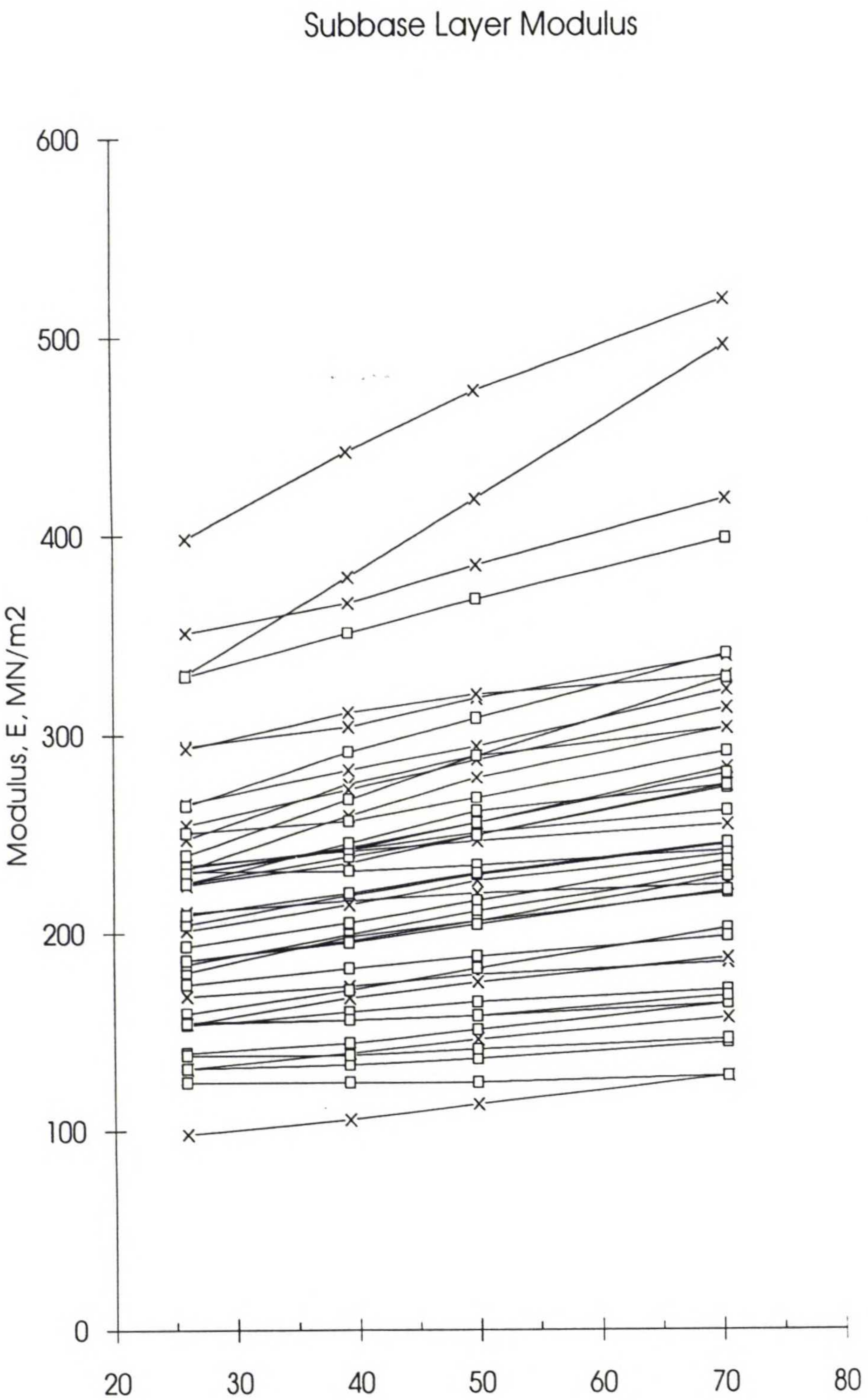


Figure 37. Finnish SHRP-LTPP study. Stress-dependency of backcalculated subbase course modulus. Elmod-program.

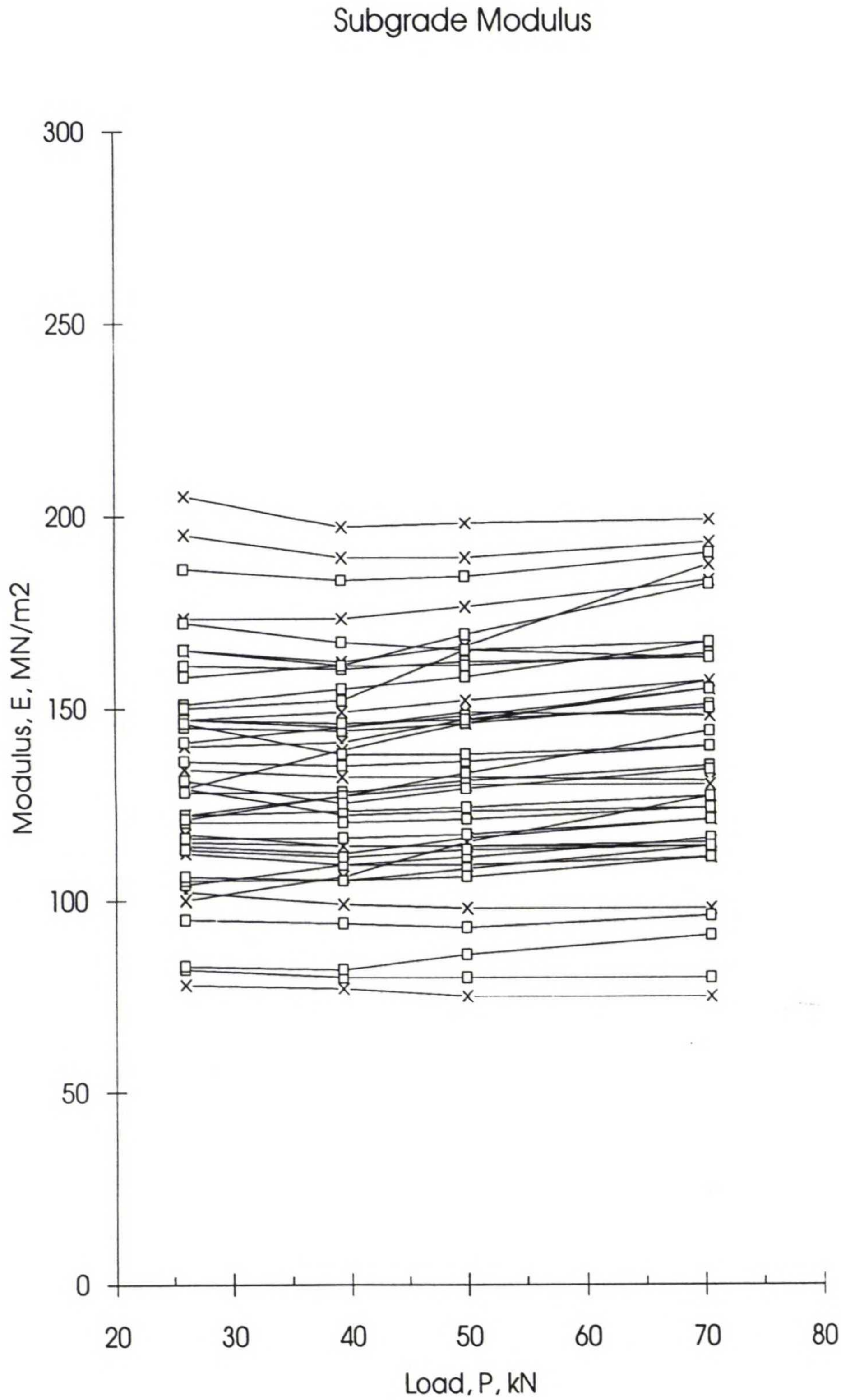


Figure 38. Finnish SHRP-LTPP study. Stress-dependency of backcalculated subgrade modulus. Elmod-program.

The moduli of granular materials used in unbound base and subbase courses generally increase with increasing load level. Granular subgrade materials should behave similarly, whereas the moduli of cohesive materials should decrease with increasing loading level due to shear stress [9]. According to Figures 32 and 36, stress-dependency is strongest with base course material. Subgrade materials seem to exhibit little or no stress-dependency. This follows from the level of stress induced in each layer. The asphalt and base course receive most of the stress from traffic or FWD loading. Finnish road structures investigated in this study are relatively thick due to frost heave design practice.

The theoretical stress level induced in layers was studied using average layer thicknesses and moduli values respective of each loading level as input to the linear elastic program (BISAR). The asphalt modulus varied between 5270 and 5420 MPa, and the base course modulus from 290 to 470 MPa. The subbase and subgrade moduli were kept constant, 250 and 100 MPa respectively, since their variation was rather insignificant from the point of view of the stress calculations. The thickness of asphalt layer was 100 mm over 200 mm base and 750 mm subbase courses.

The vertical stress at the top of the subgrade varied from 9 to 16 kPa for target load of 27 to 71 kN, respectively. Similarly, the vertical stress in the middle of the subbase layer varied from 15 to 38 kPa, and in the middle of the base layer from 60 to 167 kPa. Both the level of stress and the rate of change of stress with increasing loading level are higher in the base layer than in the subbase layer and subgrade. Thus, it can be concluded that the base layer is the most stress-sensitive of pavement layers to traffic loading. It is worth noting here that stress-dependency is of minor importance compared to the seasonal variation in the unbound layer and subgrade moduli, but is recommended that this be taken into account in determining the average layer moduli [8].

The base and subbase moduli backcalculated with Elmod are directly proportional to the loading level in all cases. This is consistent with the sieve analysis made from material samples taken from the test pits. These show that materials used in the unbound layers are all granular, and therefore expected to exhibit increasing modulus with increasing loading level. The backcalculated unbound layer moduli from the Modulus-program show a decrease with increasing loading level in some instances, which seems rather unusual. This could be due to overall uncertainty in the calculations at these sites. The backcalculation solution is such that a change in the modulus of one layer causes a change in the other layer moduli as well. As discussed before in chapter 7, an exact solution using linear theory is sought for within the Modulus-program, possibly leading to an unreasonable set of layer moduli in certain cases.

The in-situ stress state in pavement structure subjected to traffic of FWD loading is more complex and difficult to determine precisely. Horizontal and shear stresses are caused by loading, unit weight of the paving materials, and residual stresses due to compaction. Moisture content and loading time also have an effect on the induced stresses. However, the backcalculated layer moduli correlate quite well with Finnish design values for the investigated materials. In the next phase of the study, laboratory tests are to be made on material samples taken from the test pits.

9 THE EFFECT OF DIFFERENT PROGRAMS ON CRITICAL STRAINS

If the sole purpose of backcalculation is to determine the in-situ layer moduli as such, great differences will be encountered in the results from different programs, as can be seen in the previous two chapters. Usually FWD results are further used for the evaluation of need for maintenance, or development of new mechanistic-empirical models for pavement design as described in chapter 1. Critical strains are often a matter of interest. Longitudinal tensile strain at the bottom of the asphalt layer and vertical compressive strain at the top of the subgrade are usually considered as critical strains describing the fatigue properties of highway structures.

Critical strains were forward-calculated with the linear elastic program (BISAR) using the layer moduli and thicknesses from the Modulus backcalculations. These strains were compared to those calculated by Elmod. Elmod forward-calculates strains using Boussinesq's equations applied to semi-infinite half-space, calculated with the method of equivalent thicknesses (MET). The results of the comparison are seen in Figures 39 and 40.

It is observed that the strains in the great majority of sites are quite close to each other with both calculation methods, especially in the subgrade. Some outlying points are seen for the asphalt strain in Figure 39, but these can be ignored, since results from these test sections are ambiguous for moduli calculations as well. Also, the average error per sensor for these test sections is abnormally high.

The error in moduli backcalculated with Elmod is somewhat outbalanced because the method of equivalent thicknesses (MET) is also used to forward-calculate strains [3]. Therefore, it seems that if only strains, and not layer moduli, are of interest, both methods could be successfully used for the FWD measurements evaluation. However, great differences may occur in the calculated layer moduli between the different programs, as seen in previous chapters. In order to correctly interpret backcalculation results, it is essential to know what kind of results are produced by the program that is used. If, for example, it is known that the backcalculated subgrade moduli are generally too high, they may be estimated to have a somewhat smaller value than the calculated one.

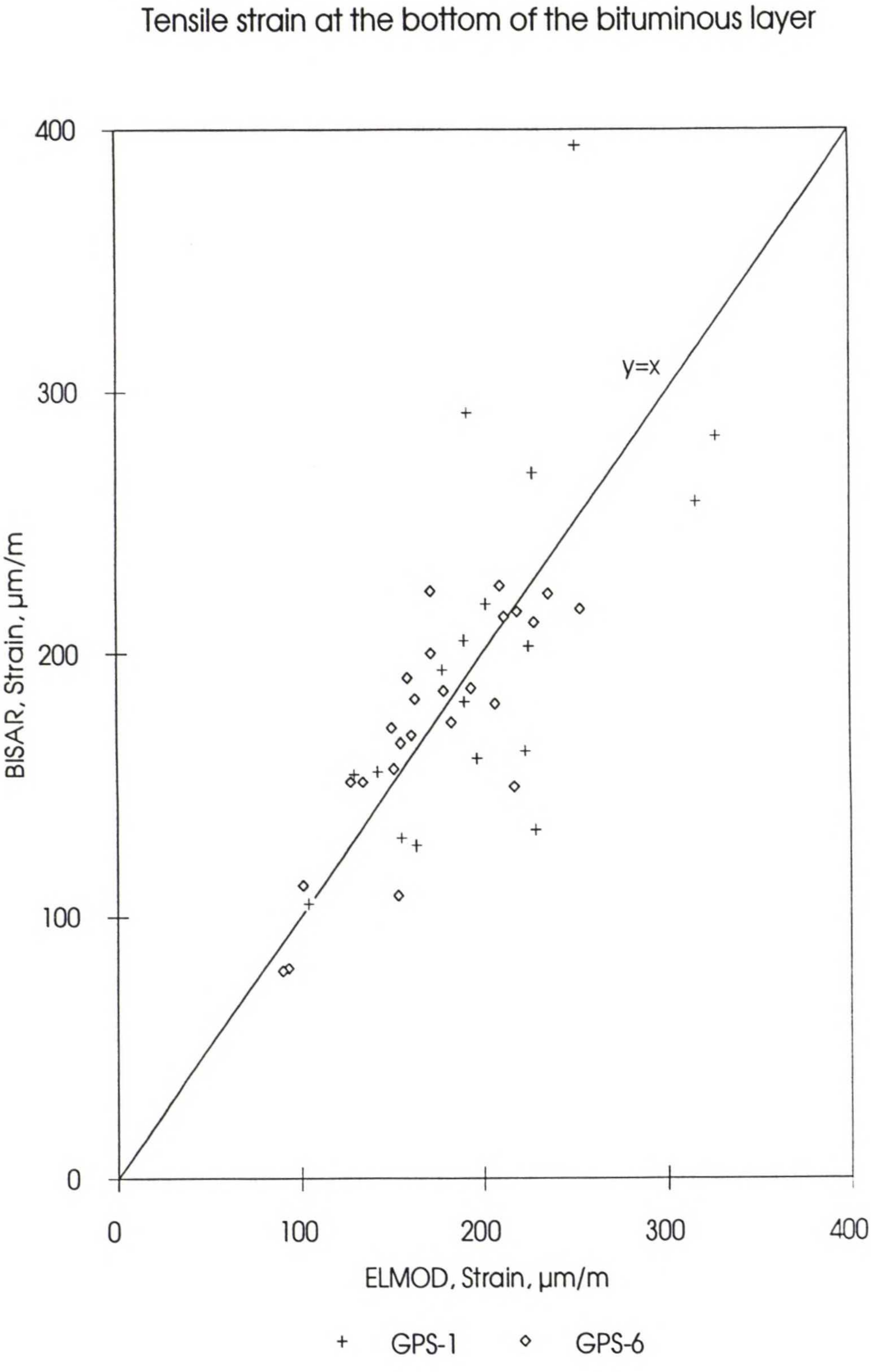


Figure 39. Finnish SHRP-LTPP study. Tensile strain at the bottom of bituminous layer. Comparison of two calculation methods.

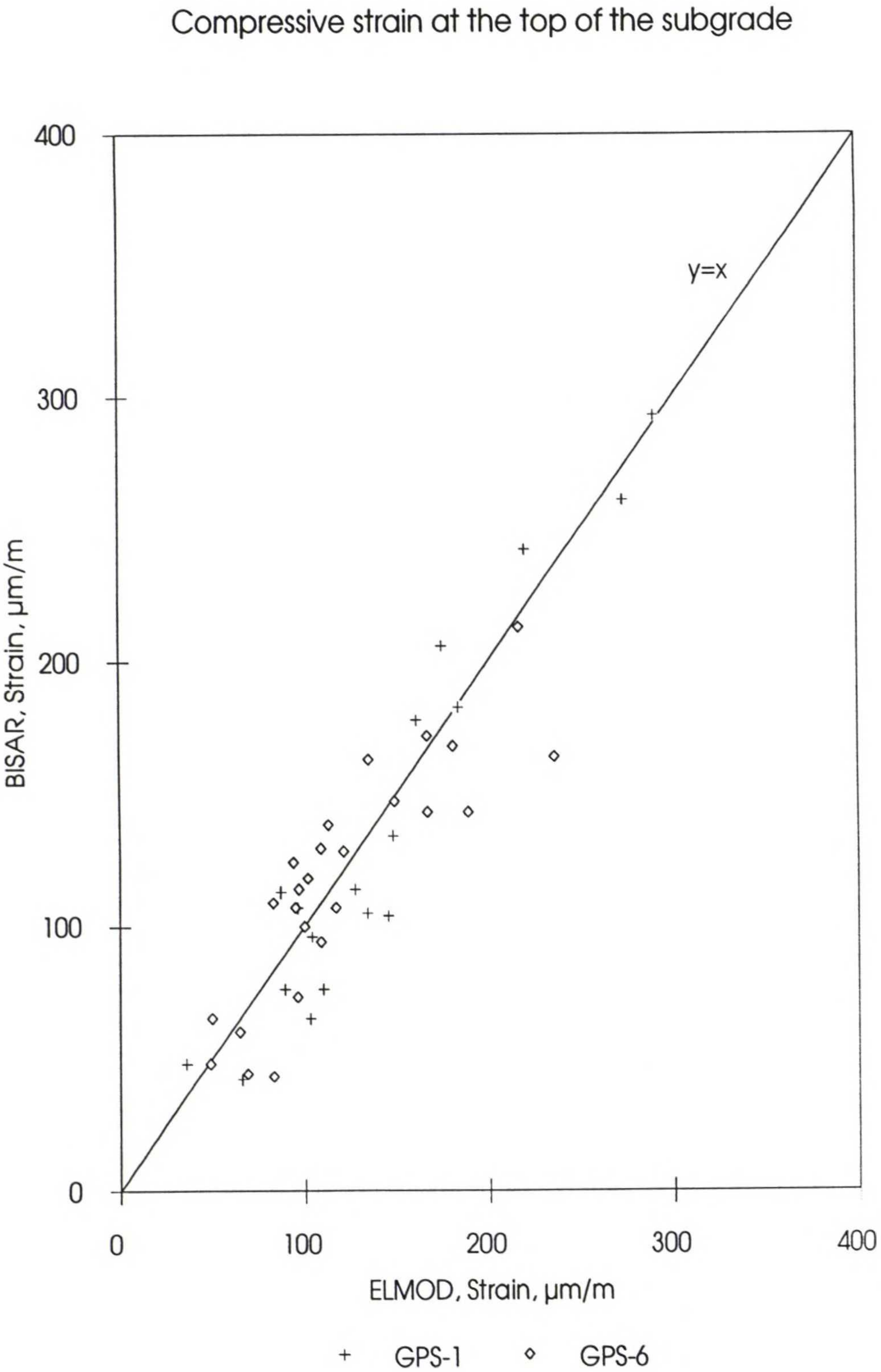


Figure 40. Finnish SHRP-LTPP study. Compressive strain at the top of the subgrade. Comparison of two calculation methods.

Verification of the calculated strains was made by comparing them with strains measured at an instrumented pavement section at the Virttaa test site. Loading for the strain measurements was provided by means of a truck with known axle load. Falling weight deflectometer measurements were made simultaneously with the strain and deflection measurements.

Two instrumented pavement structures used in this study are presented in Figure 41. The total thickness of bituminous layers is 140 mm and 60 mm for the "thick AC" and "thin AC" structures, respectively. For both structures, a granular base course with thickness of 400 mm is placed over a sandy subgrade.

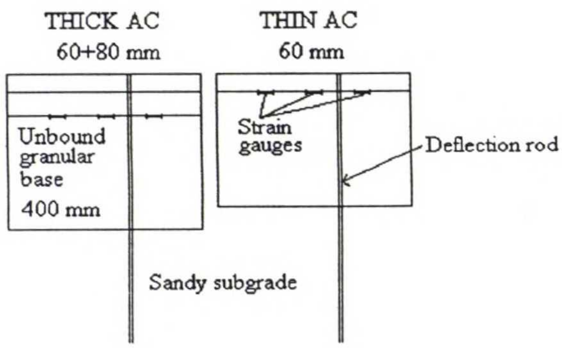


Figure 41. Virttaa test site. Schematic illustration of test structures.

The length of the test structures is ten metres. The results are derived from one to three longitudinal strain gauges and one deflection rod at each test structure. Strains were calculated with the two methods described above. Surface deflections were calculated with the linear program using the backcalculated layer moduli from the FWD measurements. Tensile strain at the bottom of the bituminous layer was compared with the measured strain and calculated surface deflection with that measured with the FWD and the deflection rod.

The measurements were carried out under two different conditions, during high temperatures in August 1992, and during the spring thaw period in April 1993. The location of freeze in spring measurements is shown in Figure 42.

Measured and calculated asphalt strains are compared in Figure 43 for summer and in Figure 44 for spring measurements. A comparison of measured and calculated surface deflections is made in Figures 46 and 47, respectively.

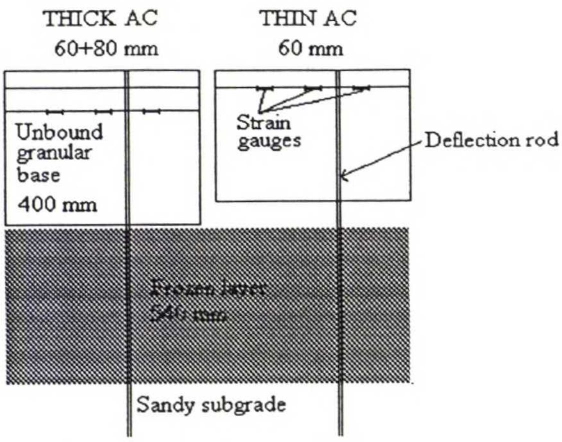


Figure 42. Virttaa test site. Location of freeze during spring measurements.

It is seen that the calculated strains from the two calculation methods are almost equal, as was also observed from the SHRP-LTPP results in Figures 39 and 40. The measured strain seems to be at a higher level. It is to be remembered, however, that the calculations were made from the FWD results and loading for strain measurements was provided by a moving wheel load.

The rather large difference between the measured and calculated strain in Figures 43 and 44 could be caused by the dynamic wheel load or the static backcalculation of FWD measurements. Due to surface roughness, a dynamic effect is added to the wheel load. The magnitude of the dynamic effect at the moment of peak strain is unknown. As previously discussed in chapter 7.1, the static analysis of the dynamic FWD measurement could cause overestimation of the pavement layer moduli. This in turn reduces the calculated strain.

The significance of correct determination of critical strain is illustrated in Figure 1. With an asphalt strain of 200 µm/m, a certain structure is calculated to carry 8.5 million load applications (standard axle loads). But if the actual strain is 300 µm/m, pavement life is reduced to 1.1 million load applications. This means that the structure will endure just one eighth of its designed life.

Tensile strain at the bottom of the asphalt layer was also measured with a strain gauge by applying FWD load on the position of the strain gauge, as shown in Figure 45. The asphalt strain was calculated from the FWD results with the Elmod- and Bisar-programs, as described above. The measured strain from the FWD loading correlates better with the calculated strain than the strain measured under a moving wheel load, as one would expect. It is to be noted here, that the

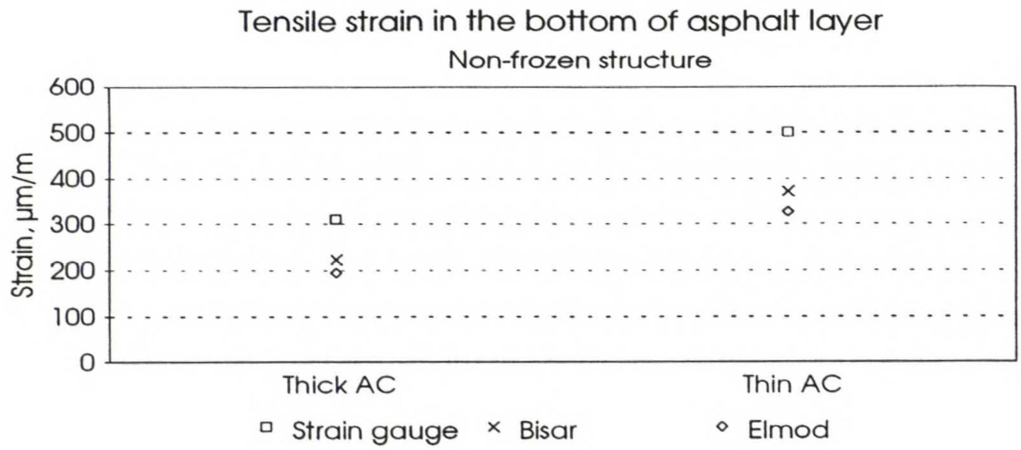


Figure 43. Measured and calculated asphalt strain in summer at virttaa test site.

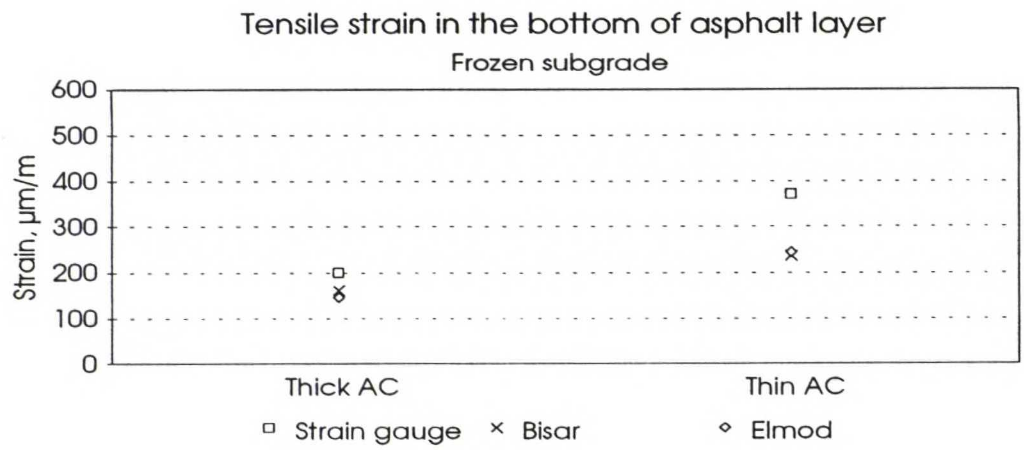


Figure 44. Measured and calculated asphalt strain during the spring thaw period at Virttaa test site. (Refer to fig. 42 for location of frozen layer in the structure.)

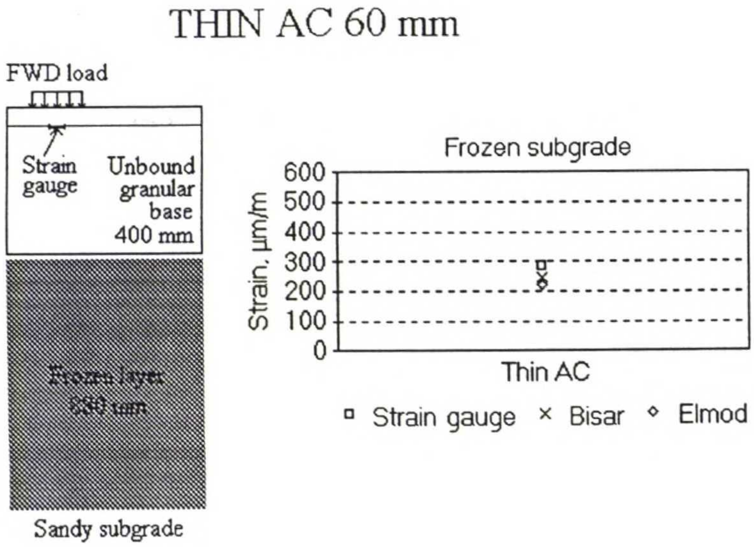


Figure 45. Virttaa test site. Measured and calculated asphalt strain from FWD load. Location of freeze during spring thaw period.

calculated asphalt strain strongly depends on the modulus of the layer. In these calculations the asphalt modulus had to be assigned a fixed value, because the layer is thin (60 mm). Changing the fixed value will affect the calculated strain.

From the deflection comparison in Figures 46 and 47 it may be concluded that deflections measured with the FWD and calculated with the linear program using backcalculated layer moduli match quite well. This should be the case when linear analysis is applied to the FWD measurements. The measured deflection is smaller than the FWD or calculated deflection in most cases. This most likely follows from the fact that the deflection rod extends to a depth of 1,5 meters, whereas the FWD measures total deflection of the structure.

In order to properly understand the relationship between the measured and calculated strains and deflections, further validation needs to be made. This will produce valuable information for the interpretation of deflection measurements.

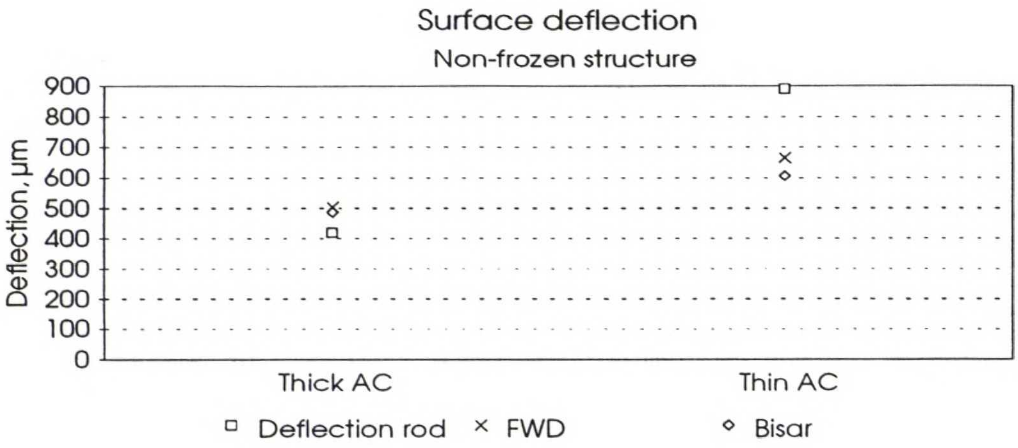


Figure 46. Measured and calculated surface deflection in summer at Virttaa test site.

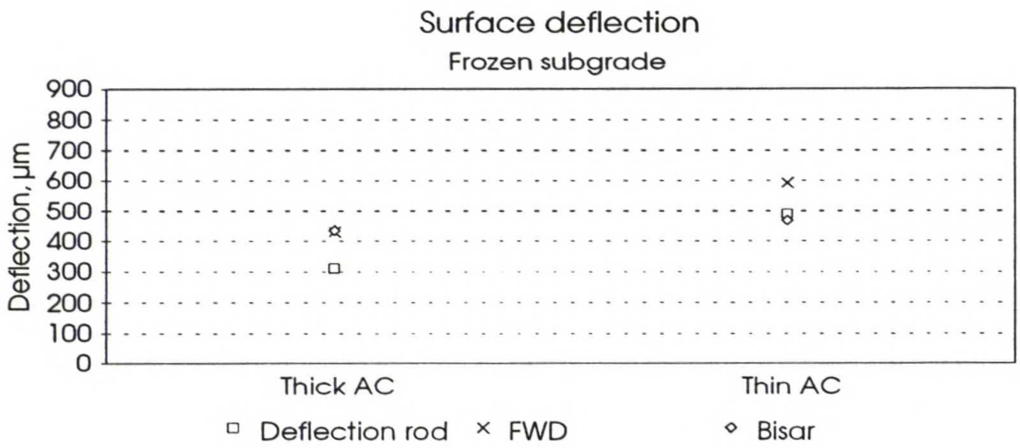


Figure 47. Measured and calculated surface deflection during the spring thaw period at Virttaa test site. (Refer to fig. 42 for location of freeze in the structure.)

10 SUMMARY AND CONCLUSIONS

Field FWD data from 43 test sections was back-analysed with the Elmod- and Modulus-programs in order to compare layer moduli from the two programs. Modulus was found to give higher AC modulus values and Elmod tended to give higher unbound layer and subgrade moduli values. The coefficient of variation (CV) of the asphalt layer modulus was found to be quite similar for both programs, around 25%. Variation in the backcalculated unbound layers and subgrade moduli was greater with Modulus than with Elmod.

The effect of stress level on layer moduli was studied using four different loading levels. The base course shows the greatest stress-dependency due to a higher stress level than that in the subbase and subgrade layers. The backcalculated moduli exhibit an increase with increasing load level for all layers, except for subgrade with Elmod. Stress-dependency is not as straightforward in the Modulus results. Subgrade behaviour seems somewhat similar with both programs. The non-linear behaviour of materials is a subject for further study involving more accurate material models.

Factors other than loading level, such as the applied static and linear backcalculation analysis, may contribute to the encountered stress-sensitivity of the asphalt layer material. For the GPS-6 sections, the degree of cracking in the underlying asphalt layer may be unknown, thus increasing deviation in the backcalculated AC moduli. Taking into account different properties of different AC layers also calls for further study.

Critical strains were calculated with linear elastic program (BISAR) using backcalculated moduli from Modulus. They were found to have similar values when compared to strains calculated with Elmod. A comparison of calculated strains with measured strains from the field showed a certain discrepancy between the two. The dynamic effect of wheel load and static back-analysis of FWD data are some of the reasons for these differences. The measured strains induced by the FWD load correlate quite well with the calculated strains.

Obtaining realistic estimates for pavement layer moduli with backcalculation requires experience and knowledge of the backcalculation system. The results are not always easy to interpret. Determining the resilient modulus (M_r) in the laboratory for validation of field data is highly recommended.

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